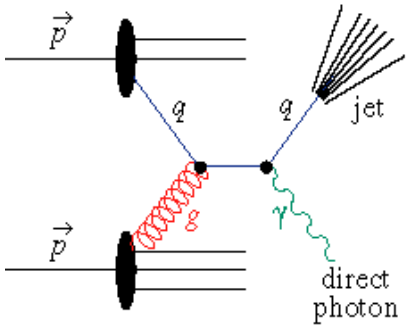
Spin Physics at RHIC



Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \rightarrow \gamma\,(+\,jet) + X$$

hard-scattering (Þ pQCD) with spin

- Physics goals of RHIC spin program
- Summary of RHIC run 2: first polarized proton collisions
- Plans for RHIC run 3

L.C. Bland
Brookhaven National Lab

On behalf of the RHIC spin collaboration

RHIC Spin Collaboration Organization

- **RHIC Spin Collaboration** (Spokesman: G. Bunce)

Develops overall spin plan; forum to coordinate spin issues for RHIC accelerator and experiments.

Spin physics is an integral part of the goals of the STAR, PHENIX and pp2pp experiments.

- **RHIC Accelerator Spin Group** (Spokesman: T. Roser, Project Manager: W. Mackay)

Accelerator physics for spin (Siberian Snakes, Spin Rotators, `Spin Flipper'); polarized ion source; polarimeters.

- **RIKEN and RIKEN/BNL Research Center** (Group Leaders: H. En'yo, G. Bunce, N. Saito)

Funds spin physics equipment; develops polarimetry; organizes spin workshops; supports young physicists.

- **STAR Spin Physics Working Group** (Conveners: L. Bland, G. Eppley)
- **PHENIX Spin Physics Working Group** (Conveners: Y. Goto, M. Perdekamp)
- **pp2pp Experiment** (Spokesman: W. Guryn)
- **BNL Groups: RHIC Spin Group** (Group Leader: G. Bunce); **Spin Theory**

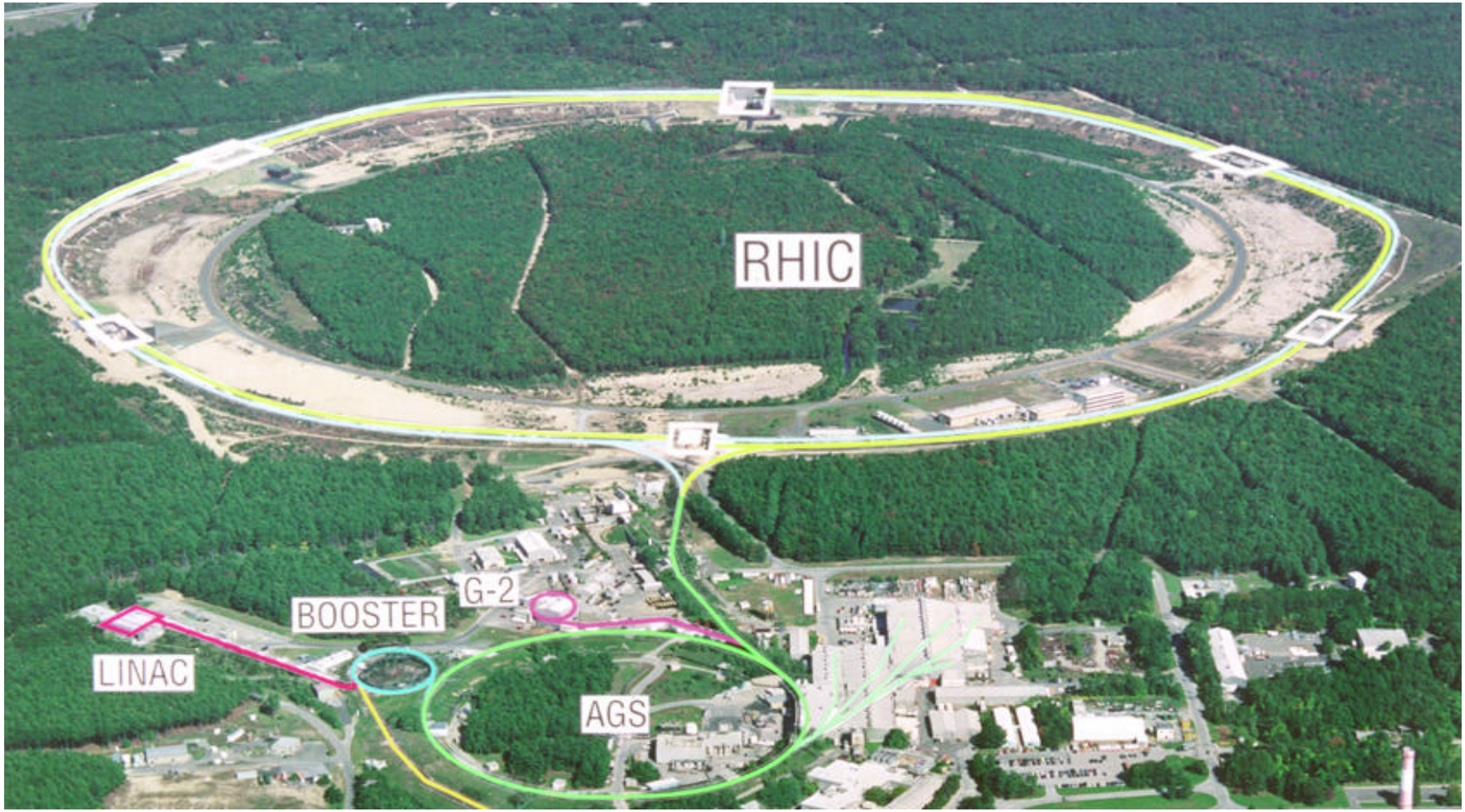
Develop / exploit spin capability of RHIC; coordinates accelerator / experiment activities; complete measurements; members in STAR, PHENIX and pp2pp experiments.

- **Laboratory / University participation**

Argonne National Lab., Brookhaven National Lab., Budker Inst., Indiana Univ., Iowa State Univ., IHEP, ITEP, JINR, Kyoto Univ., Lawrence Berkeley National Lab., Los Alamos National Lab., New Mexico State Univ., Oak Ridge National Lab., Penn State Univ., Rice Univ., Stony Brook Univ., Texas A&M Univ., Tokyo Institute of Technology, UCLA, Univ. of California (Riverside), Univ. of New Mexico, Univ. of Texas (Arlington), Univ. of Texas (Austin), Wayne State Univ., Univ. of Wisconsin, Yale Univ.

BROOKHAVEN NATIONAL LABORATORY

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

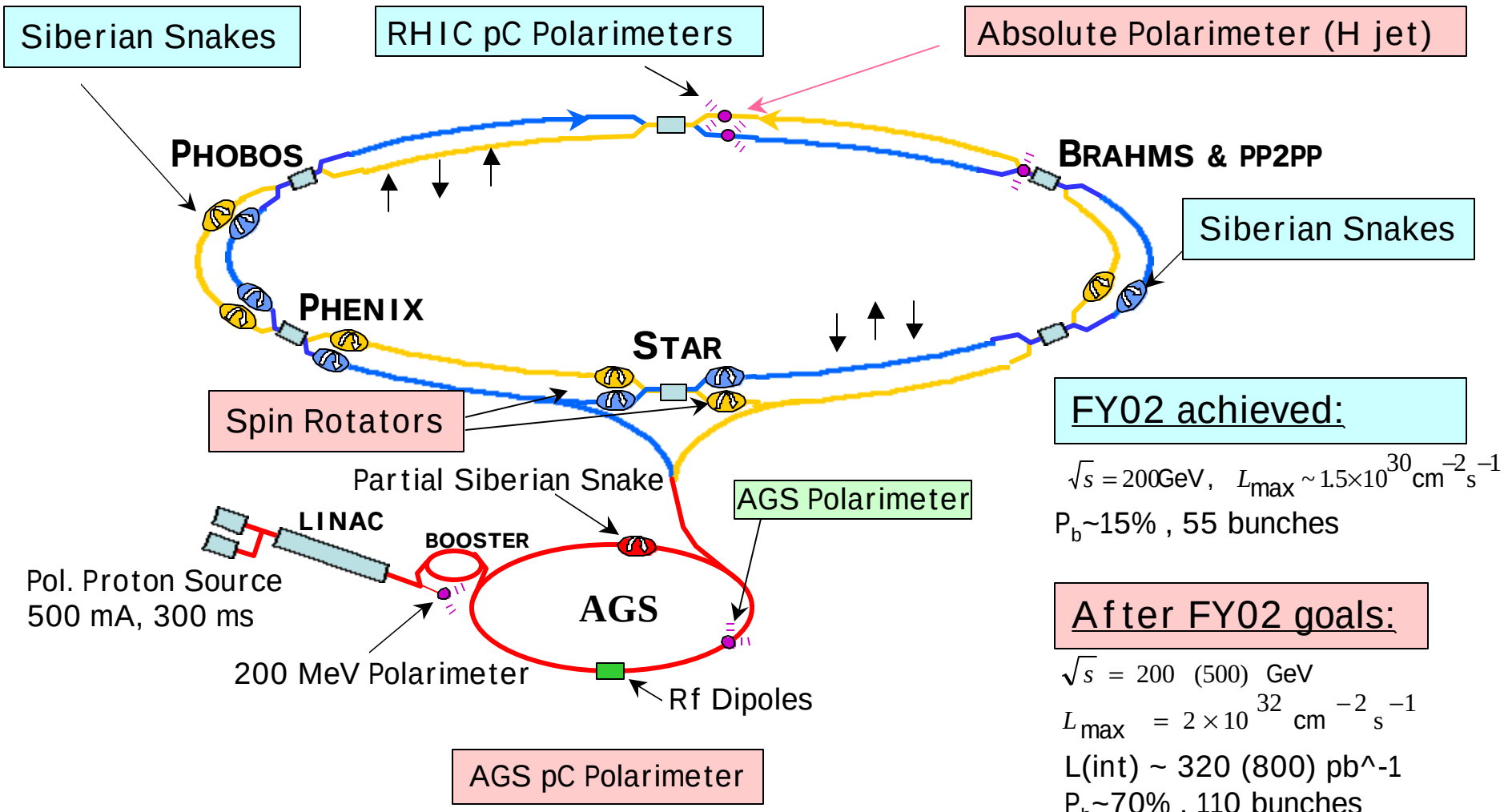


BROOKHAVEN
NATIONAL LABORATORY

(First) Polarized Proton-Proton Collisions at RHIC

FY02 devices

After FY02



FY02 achieved:

$\sqrt{s} = 200\text{GeV}$, $L_{max} \sim 1.5\times10^{30}\text{cm}^{-2}\text{s}^{-1}$

P_b~15% , 55 bunches

After FY02 goals:

$\sqrt{s} = 200\ (500)\ \text{GeV}$

$L_{max} = 2\times10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$

L(int) ~ 320 (800) pb^-1

P_b~70% , 110 bunches

See H. Huang talk

BROOKHAVEN NATIONAL LABORATORY

Where is the spin of the proton?

q(q̄) contribution — gluon contribution

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

orbital angular momentum

At present, the gluon contribution to the proton spin (ΔG) is known only poorly from scaling violations in polarized deep inelastic scattering, spanning a small range of Q^2.

$\Rightarrow$ Require a NEW GENERATION of experiments to determine ΔG.

$\Rightarrow$ RHIC Spin

- determine the *gluon contribution* to the proton's spin
- determine the *flavor decomposition* of the *quark* (*antiquark*) *polarization*
- probe *transversity*: the unknown, remaining leading-twist structure function

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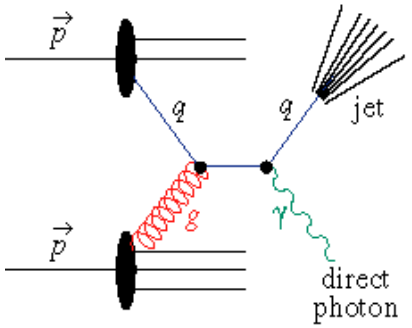
Gluon Contribution to the proton's spin

qg Compton scattering with polarized protons provides a direct measure of gluon polarization.



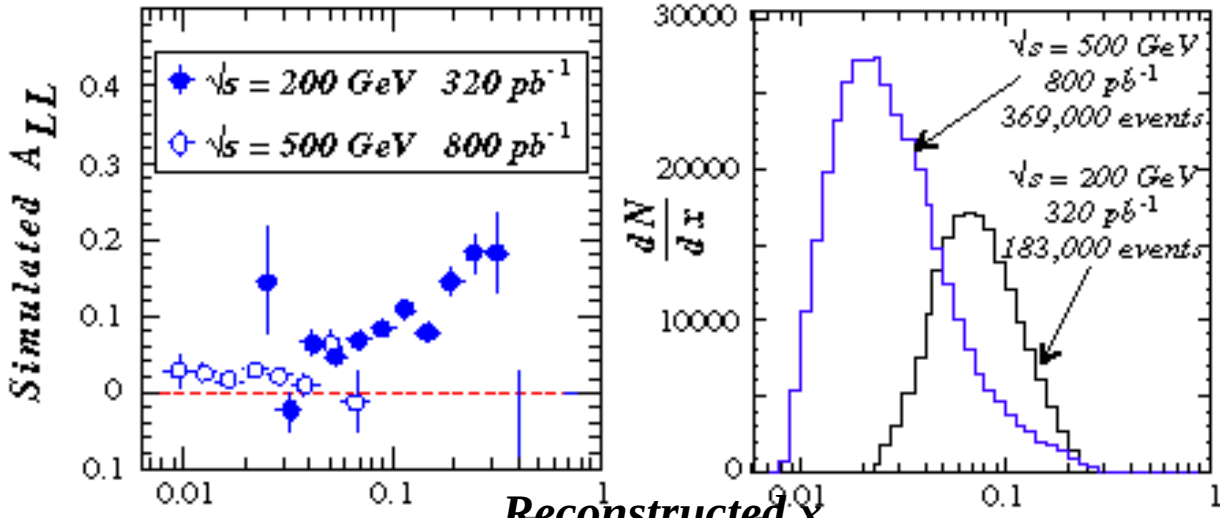
Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \rightarrow \gamma\,(+\,jet) + X$$

Coincident detection of γ and away-side jet ⇒ event determination of initial-state partonic kinematics.

$$\vec{p}\,\vec{p} \rightarrow \gamma + jet + X$$

STAR spin



Reconstructed x_{gluon}

Interpret measured asymmetry within leading-order pQCD

$$A_{LL} = \overbrace{P_{part.\,1}\,P_{part.\,2}}^{parton\ pol'ns.}\ \hat{a}_{LL} = \overbrace{\frac{\Delta f_1}{f_1}\frac{\Delta f_2}{f_2}}^{pol\ struct\ fncs.}\ \underbrace{\hat{a}_{LL}(\hat{s},\hat{t},\hat{u})}_{QCD\ Compton} \rightarrow \frac{\Delta G(x_g)}{G(x_g)}\,A_1^p(x_q)\,\hat{a}_{LL}$$

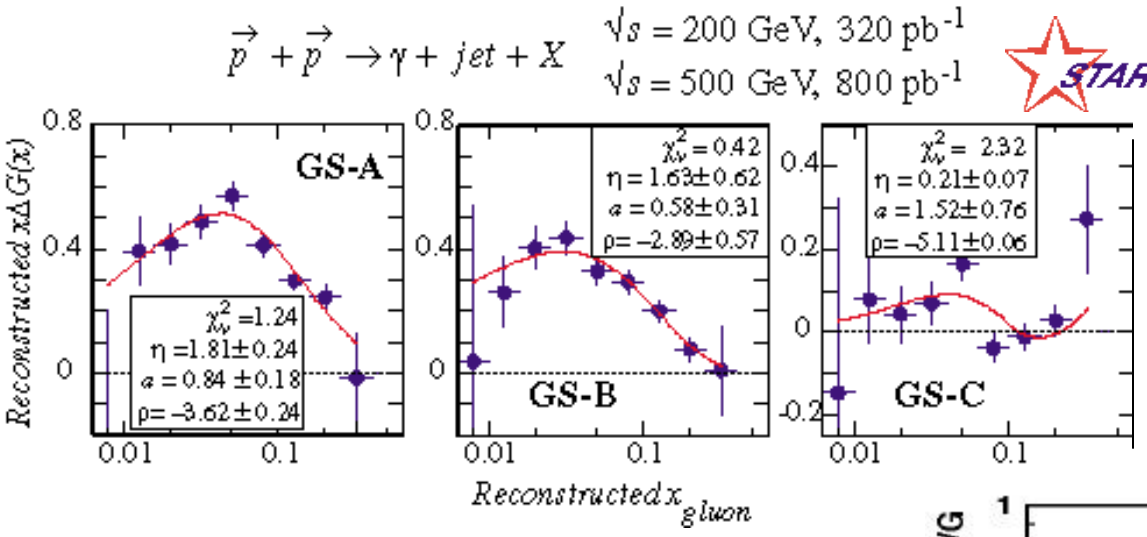
unpol struct fncs.

pQCD result for specific process

gluon polarization

Measured in polarized deep-inelastic scattering

Sensitivity to Gluon Polarization at RHIC



RHIC spans a broad range of x_{gluon}

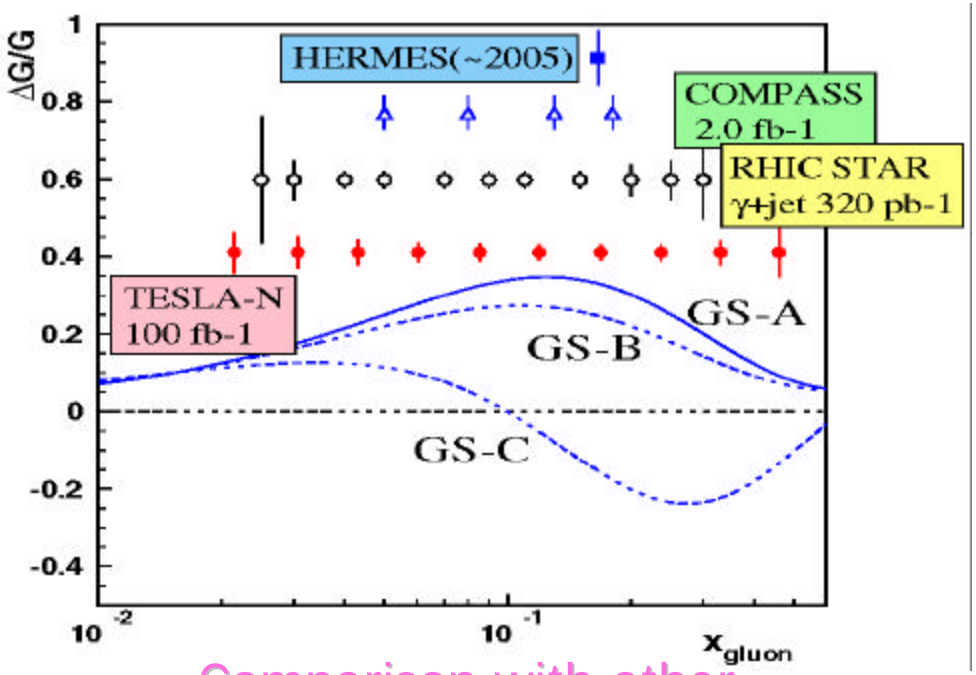
⇒ determine integral ΔG

⇒ gluon contribution to proton spin.

PHENIX and STAR will also be sensitive to ΔG through many different channels:

inclusive γ, inclusive jets, J/ψ production, heavy flavor production, etc.

⇒ check consistency of results.



Comparison with other experiments

BROOKHAVEN NATIONAL LABORATORY

Flavor Structure Sensitivity:

N. Bruner,UNM

$$\vec{p}p \rightarrow W^{\pm}$$

for $x_1 >> x_2$ (larger y_W):

$$A_L^{W^+} \sim \frac{\mathbf{Du}(x_1)}{\mathbf{u}(x_1)}$$

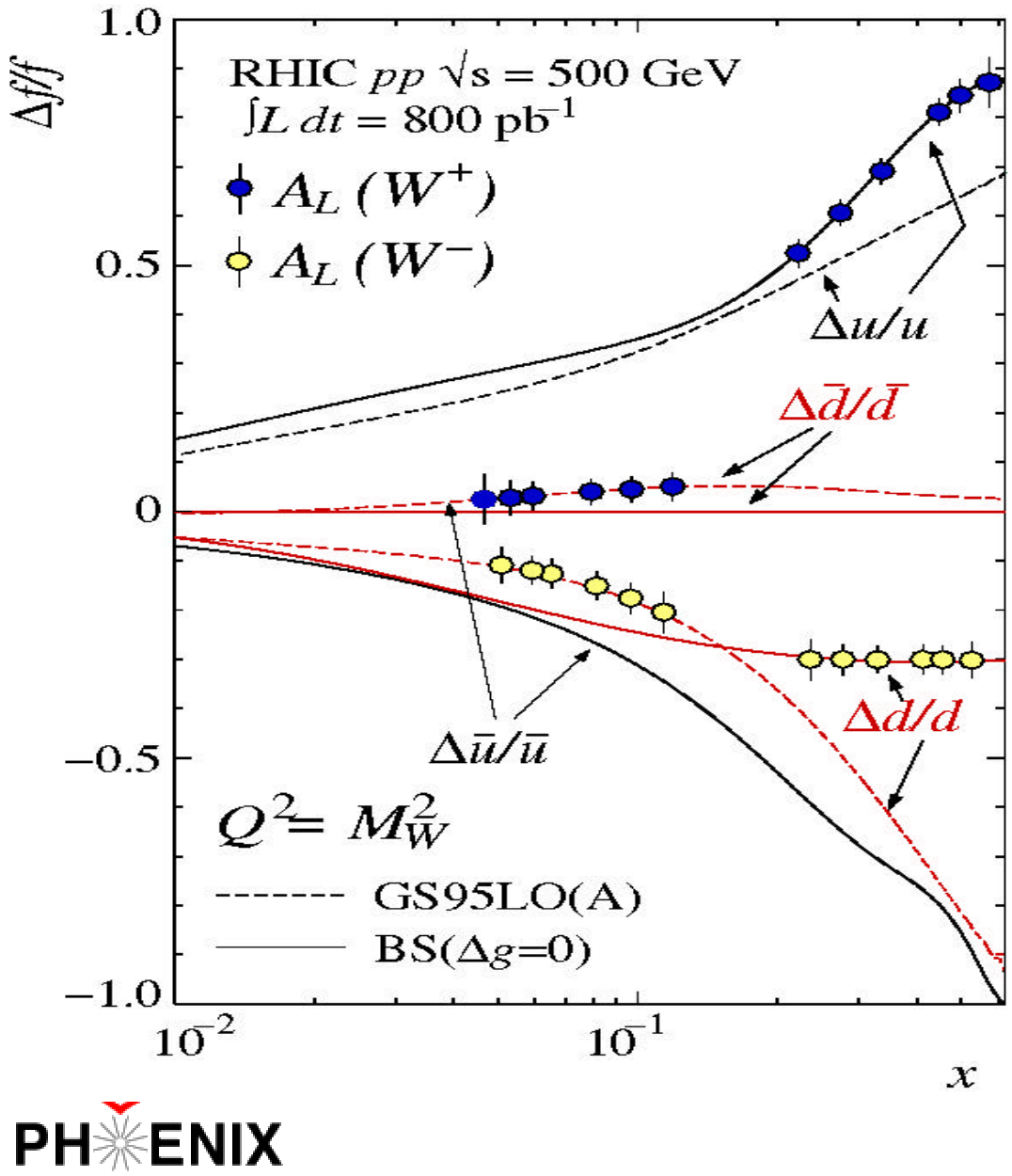
$$A_L^{W^-} \sim \frac{\mathbf{Dd}(x_1)}{\mathbf{d}(x_1)}$$

for $x_2 >> x_1$:

$$A_L^{W^+} \sim \frac{-\mathbf{D\bar{d}}(x_1)}{\mathbf{\bar{d}}(x_1)}$$

$$A_L^{W^-} \sim \frac{-\mathbf{D\bar{u}}(x_1)}{\mathbf{\bar{u}}(x_1)}$$

for explicit x and y_W see
C. Bourrely and J.Soffer,
Nucl. Phys. B445 341-379 (1995)



PHENIX

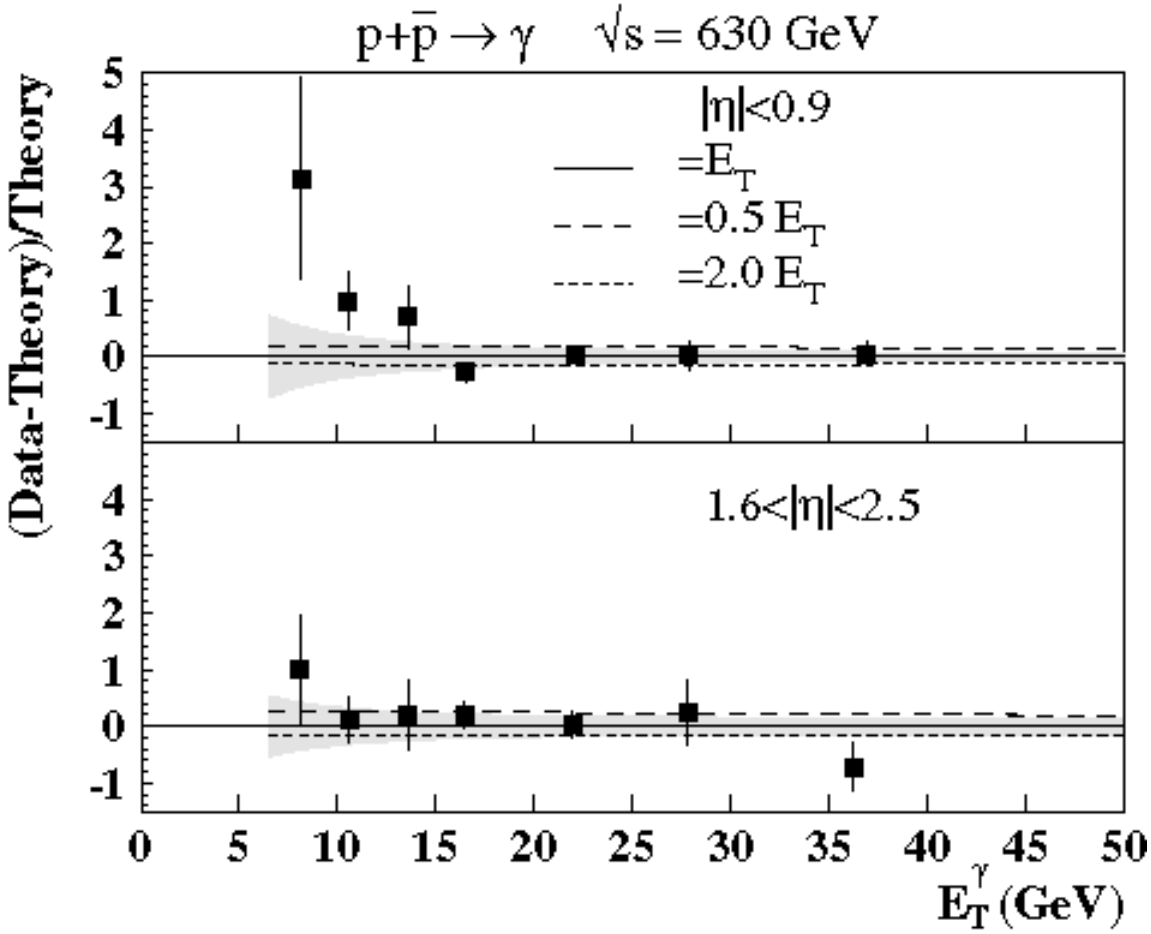
How well does pQCD describe collider data?

Prompt Photons

D0 collaboration,

Phys. Rev. Lett. 87 (2001) 251805

- NLO pQCD calculations using CTEQ5M parton distributions.
- Good agreement found between data and theory.

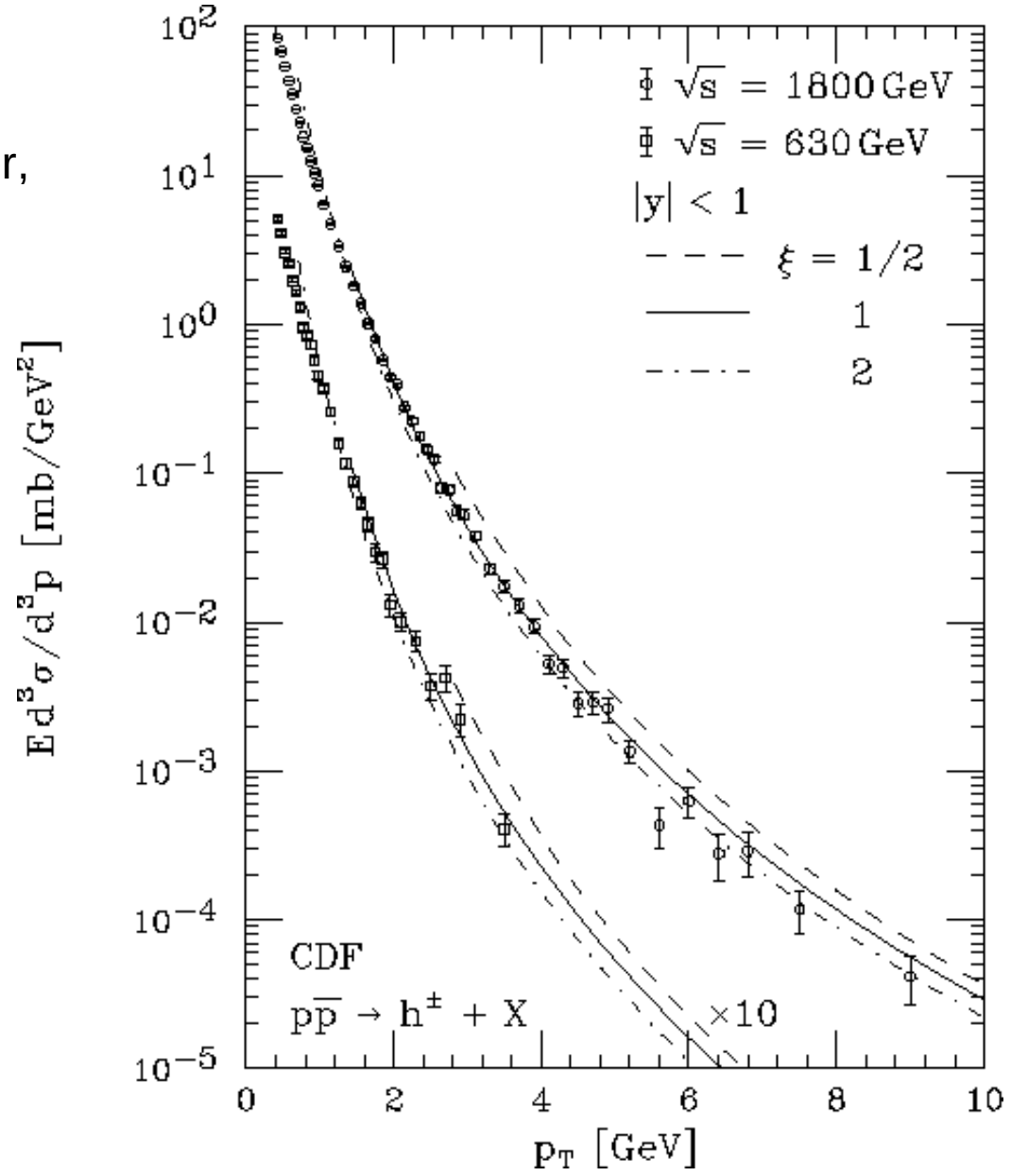


How well does pQCD describe collider data?

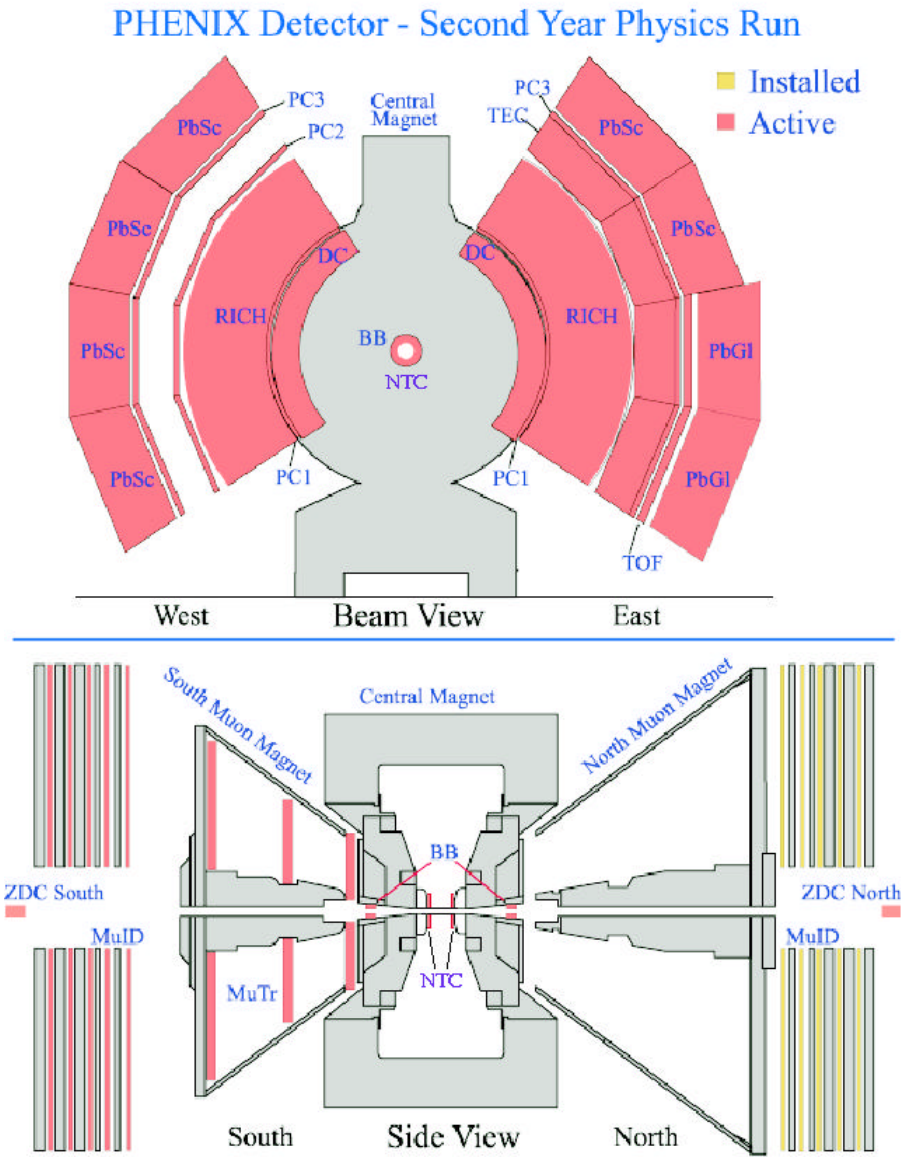
Inclusive Charged Hadrons

B.A. Kniehl, G. Kramer and B. Pötter,
Nucl. Phys. B597 (2001) 337.

- NLO pQCD calculations using CTEQ5M parton distributions.
- Good agreement found between data and theory.



PHENIX Detector Configuration in Run-2

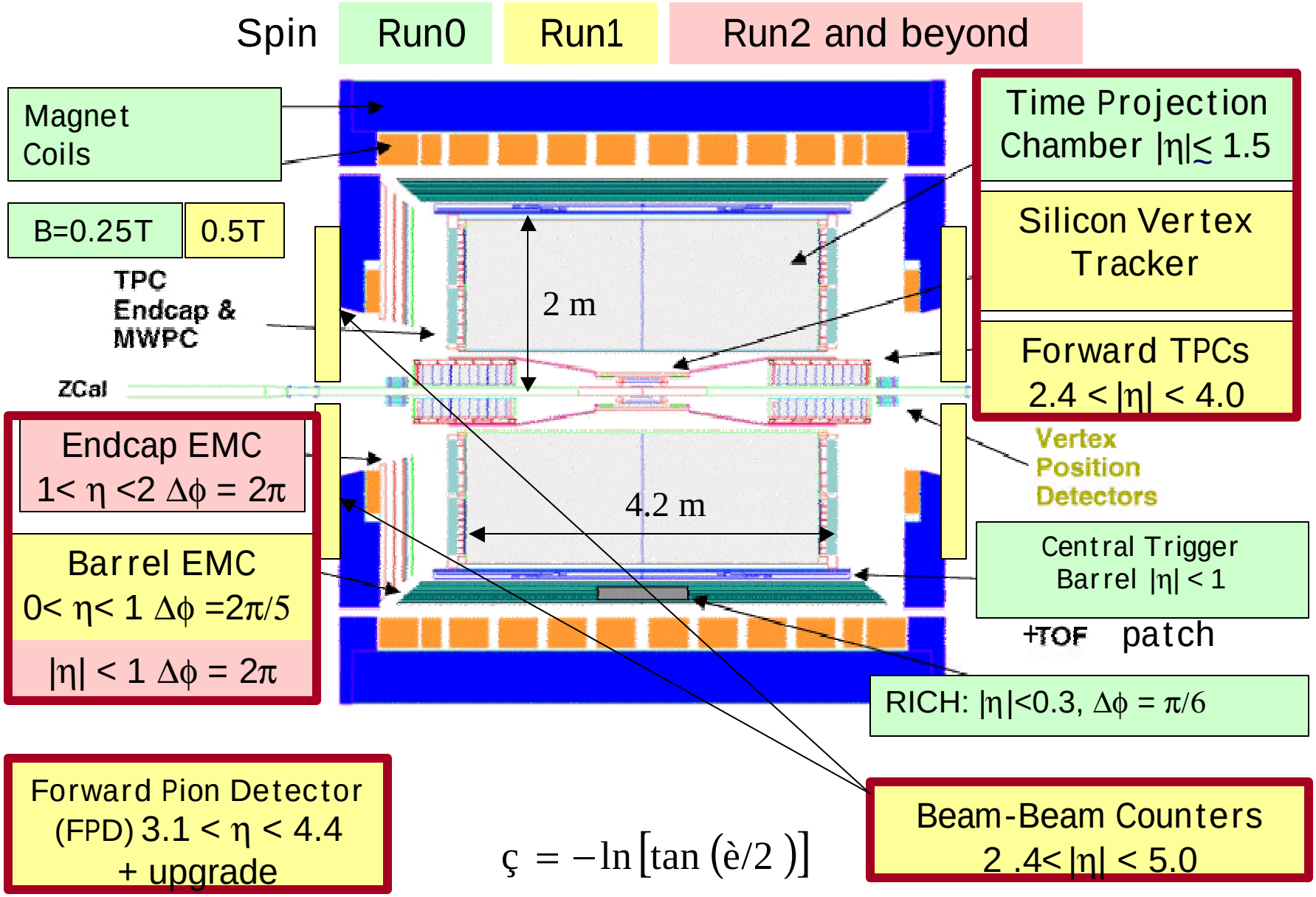


- Full Central Arms
  - –high-p_T EMCal trigger
- South Muon Arm
  - –μ-ID trigger

➔ Muon North Arm will start operation in Run-3

PHENIX

STAR – Solenoid Tracker At RHIC



$$\eta = -\ln\left[\tan\left(\theta/2\right)\right]$$

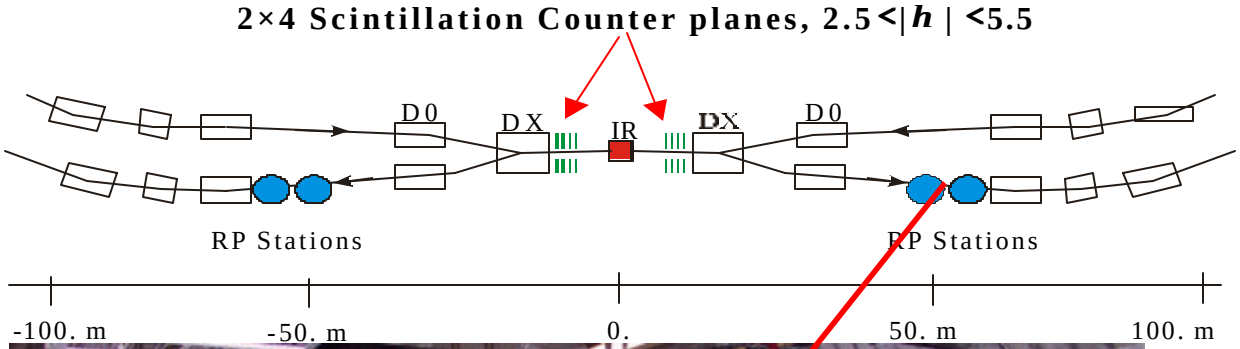
PP2PP Experiment at RHIC

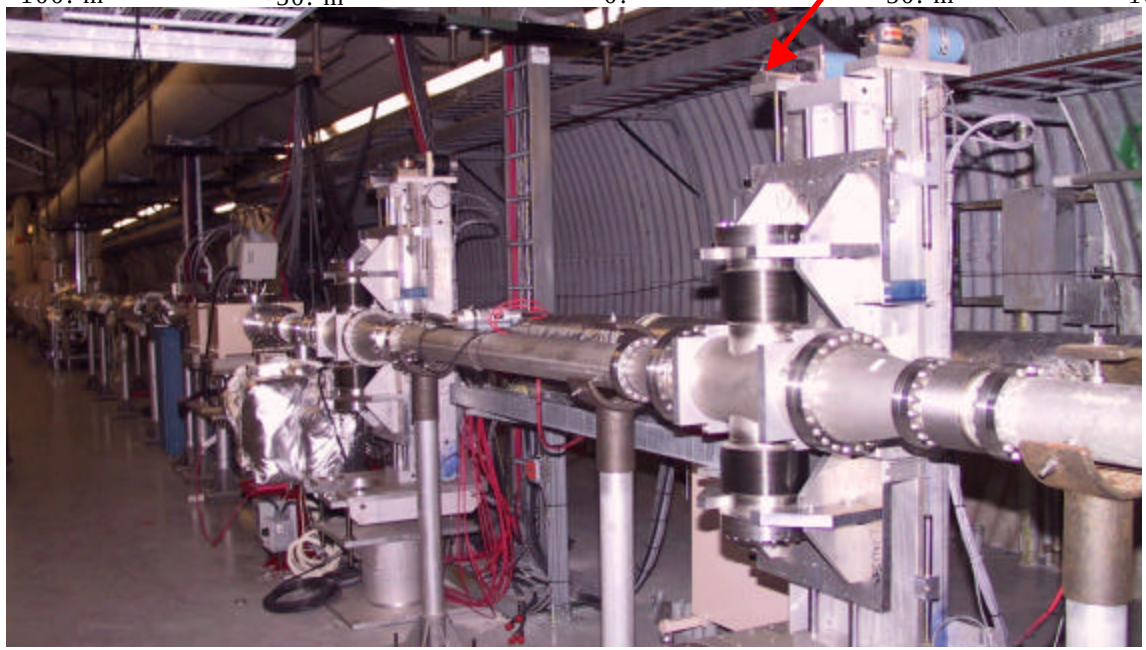
Goal is to measure spin dependence of proton-proton elastic scattering in an unexplored region of **s and -*t***

CNI region: **$0.0004 < -t < 0.02$ (GeV/c)^2 s = 200 GeV**

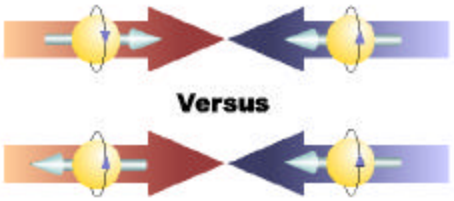
$0.0004 < -t < 0.13$ (GeV/c)^2 s = 500 GeV

Medium |t| region: **$0.02 < -t < 1.3$ (GeV/c)^2 s = 500 GeV**





Spin Asymmetry Measurements



$$A_{LL} = \frac{(s_{++} + s_{--}) - (s_{+-} + s_{-+})}{(s_{++} + s_{--}) + (s_{+-} + s_{-+})}$$

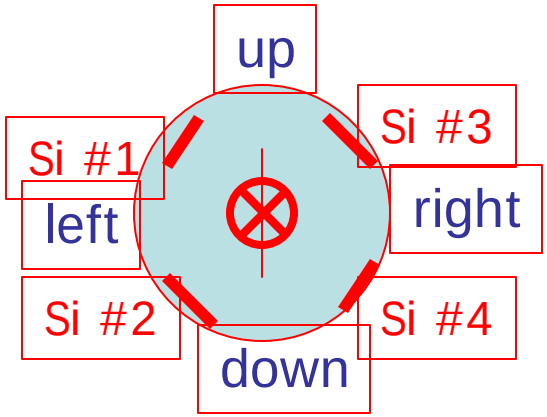
Measure spin-correlation parameter (A_{LL}) with longitudinally polarized protons

$$P_{b1} P_{b2} A_{LL} = \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

Require concurrent measurements:

- magnitude of beam polarization, $P_{b1(2)}$
- direction of polarization vector at interaction point (after spin rotator)
- relative luminosity for bunch crossings of different luminosity (R=$\mathbf{L}_{++}$ / $\mathbf{L}_{+-}$)
- spin dependence of process of interest (N_{++},N_{+-})

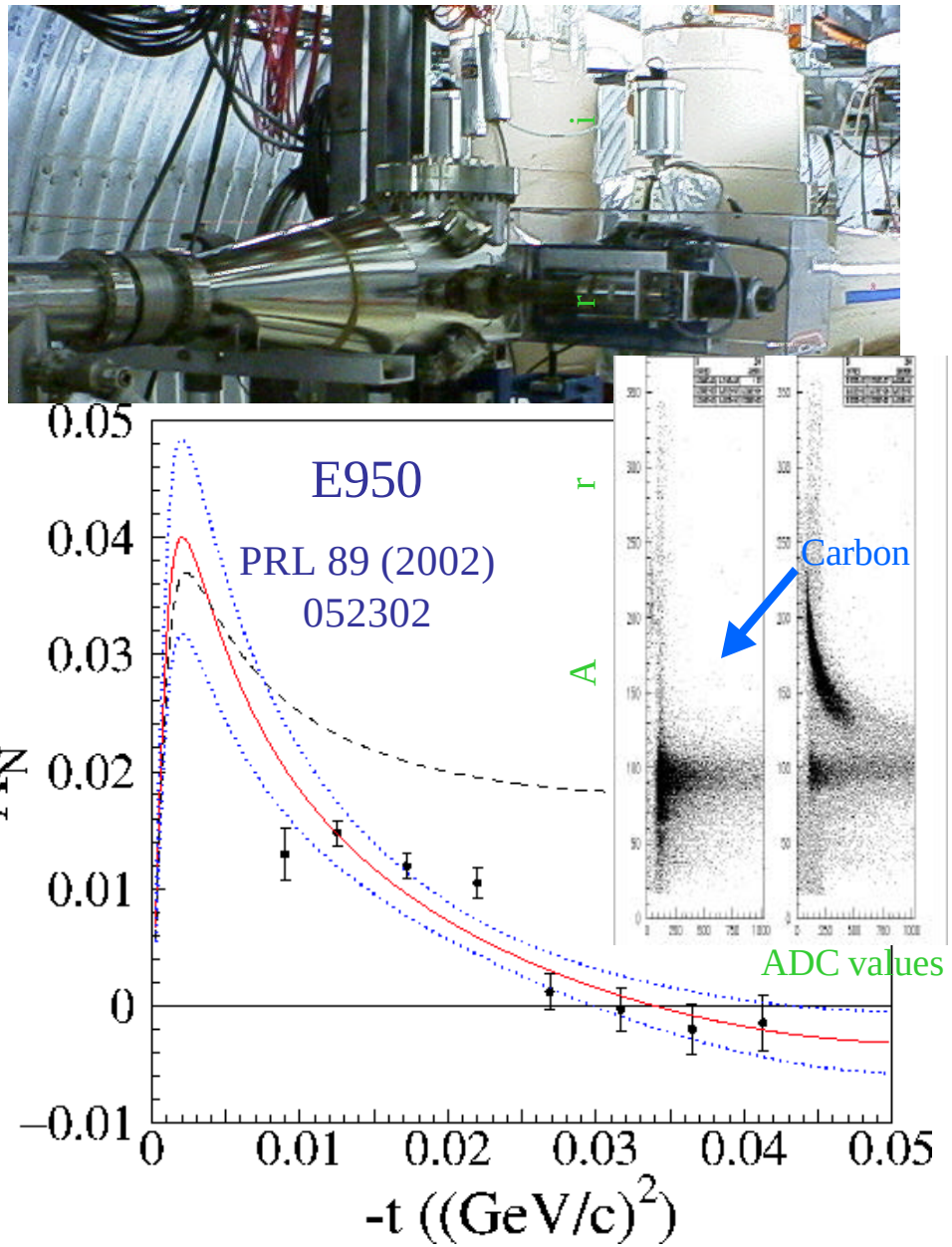
Coulomb Nuclear Interference (CNI) Polarimeter at RHIC



Beam's View

p+^{12}C CNI elastic scattering:
Recoil Carbon Detection

- Carbon filament target (5**m**g/cm^2 × 10 μm) in the RHIC beam.
- Measure recoil carbon ions at θ_{Lab}~90° having energies, 100 keV < E_{carbon} < 1 MeV .
- Measure E and TOF to identify recoil carbon ions, determine 4-momentum (-t) and determine left-right/up-down asymmetries.
- All data analysis performed on wave-form digitizer board to allow high counting rates (~0.5 MHz) via scaler measurement
  ⇒ δε ~ 3×10^{-4} in ~1 minute.



O. Jinnouchi (RIKEN) and I. Akekseev (ITEP)
SPIN 2002

Goals for Run 2 Polarized Proton Run

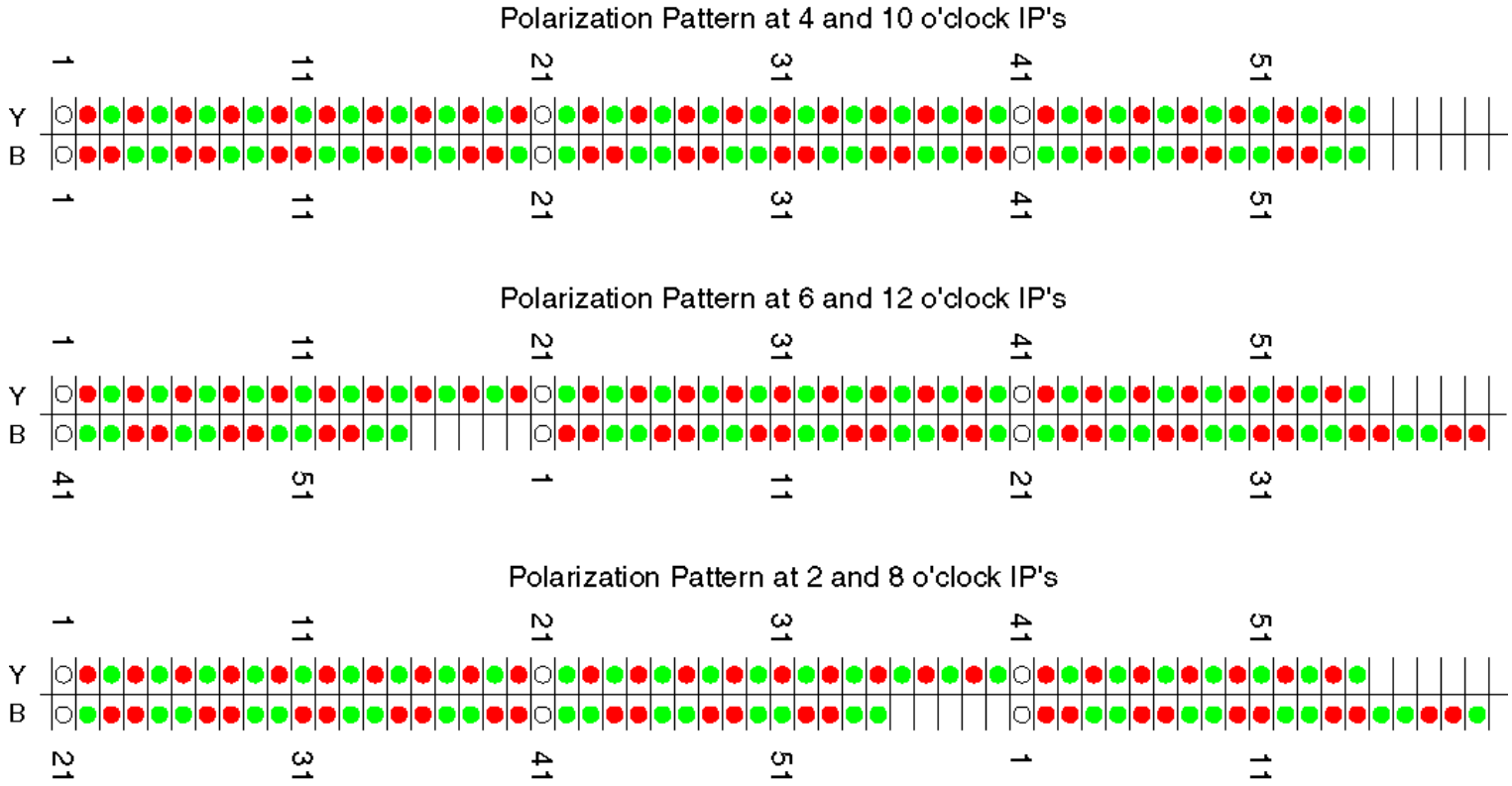
- Commission detectors for polarized pp collisions.

- Obtain reference pp scattering data set for heavy-ion program.

- Make the first measurements of polarization observables in a polarized pp collider.

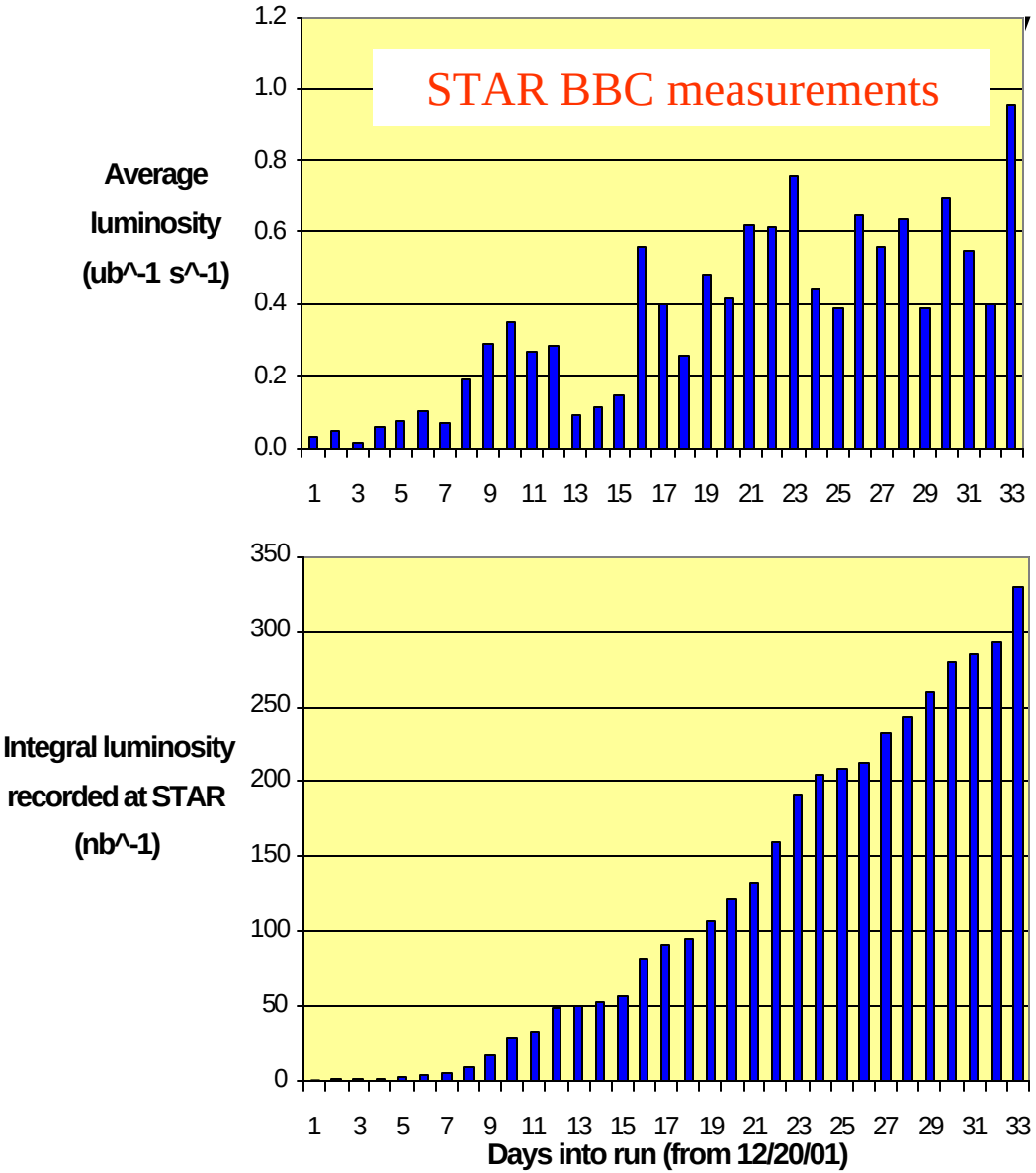
- Understand the limiting systematic errors for A_{LL} measurements.

Polarization Pattern/Timing



- Different spin combination every 214 nsec ⇒ reduce systematic errors.
- ~47 polarization reversals *before* RHIC injection.
- Because of snake magnets, *same bunch* has *opposite polarization* at IP6 and IP12.⇒ 5×10^9 *polarization reversals* in RHIC for ~10 hour store.
- Requires extremely careful timing adjustments for both RHIC and exp’ts.
- Essential to sort all data by which bunch pair interacts at experiments.

RHIC Luminosity for FY02 Polarized pp Run



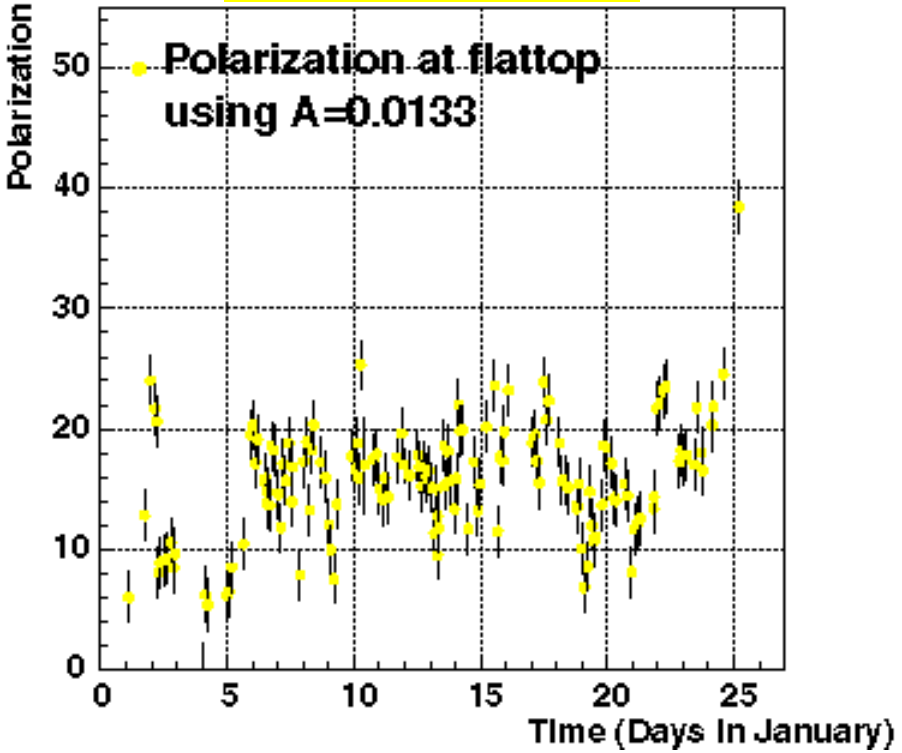
Good News…

- RHIC can deliver 10^{30} $cm^{-2}s^{-1}$.
- 110 bunches and β^*=1m possible.

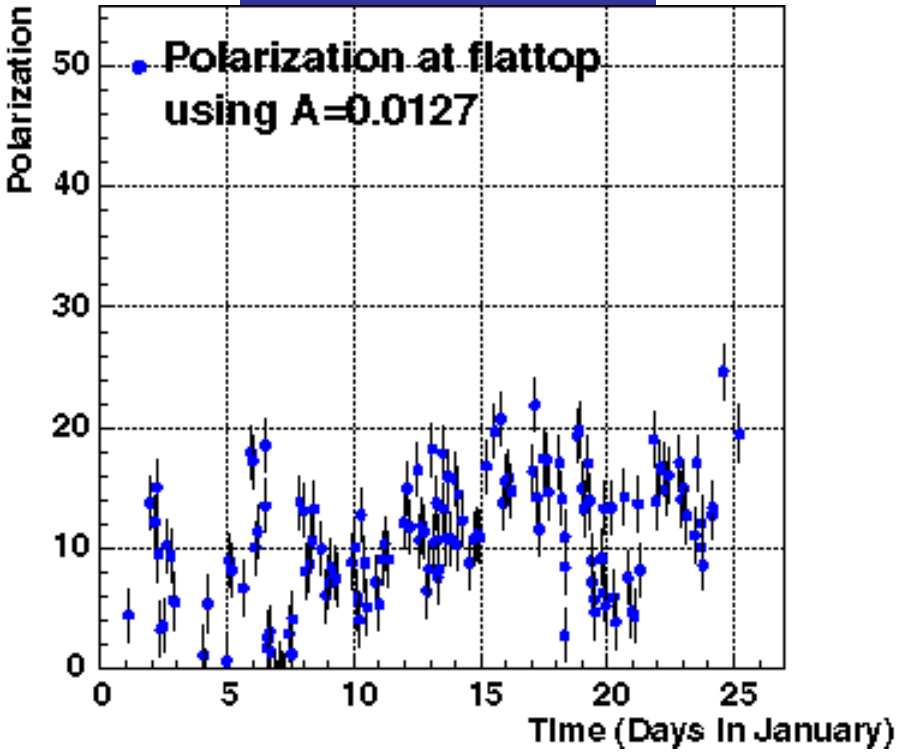
$\Rightarrow$ order of magnitude increase

RHIC Polarization at 100 GeV/c during Run 2

Yellow Ring

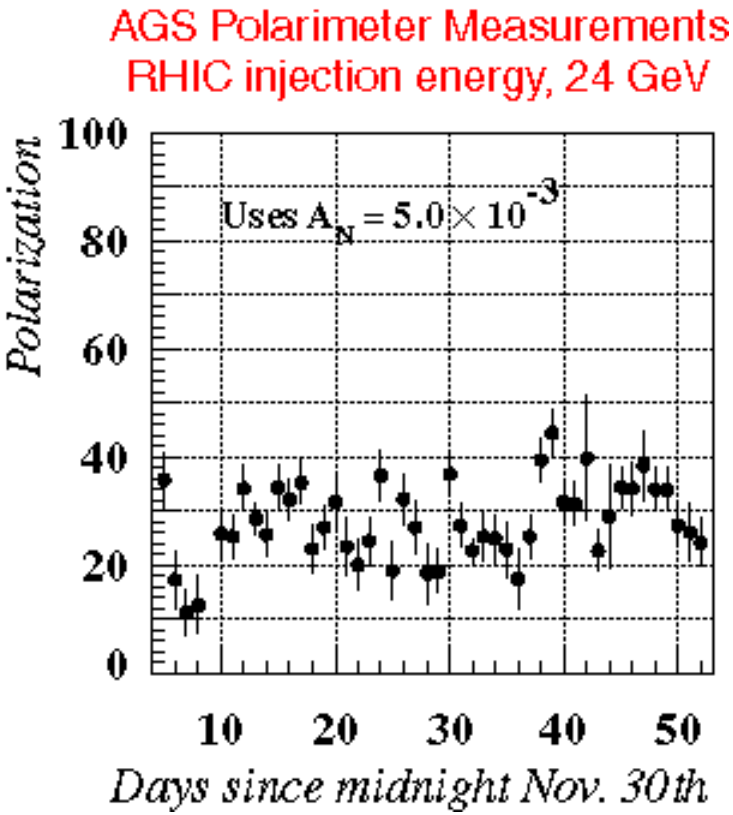


Blue Ring



First polarized *pp* collider.

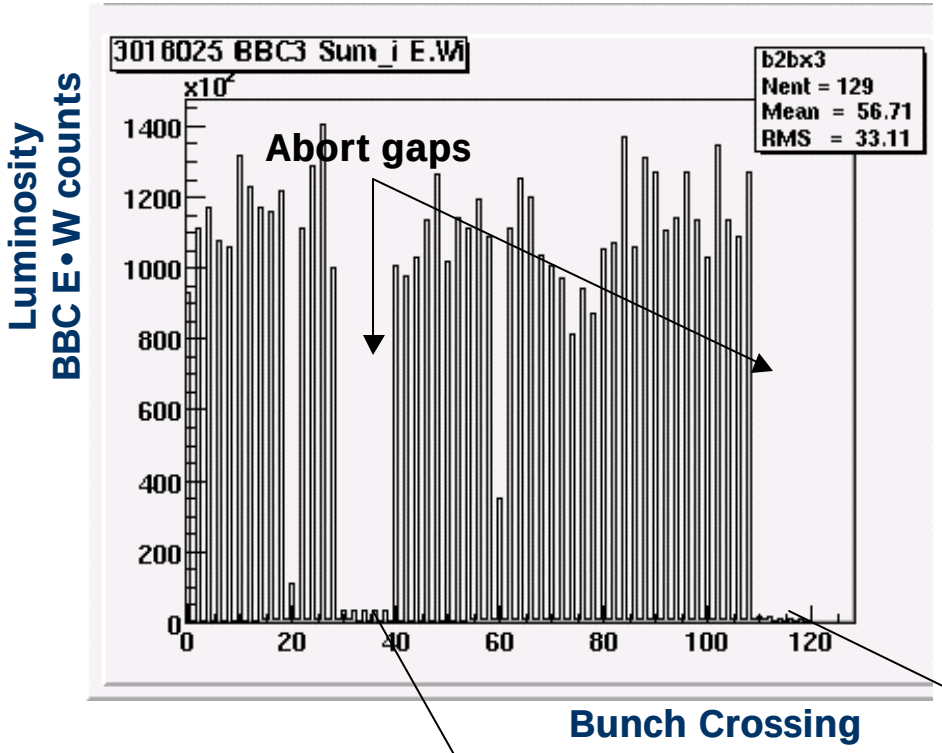
Why was the polarization so small?



- AGS dedicated to polarization tuning from the mid-November.
- Failure of Siemens motor generator for AGS reduced ramp rate by $\times 2$, increasing depolarizing resonance strengths by $\times 2$.

Data compilation: H. Spinka (ANL), R. Cadman (ANL), B. Surrow (BNL)

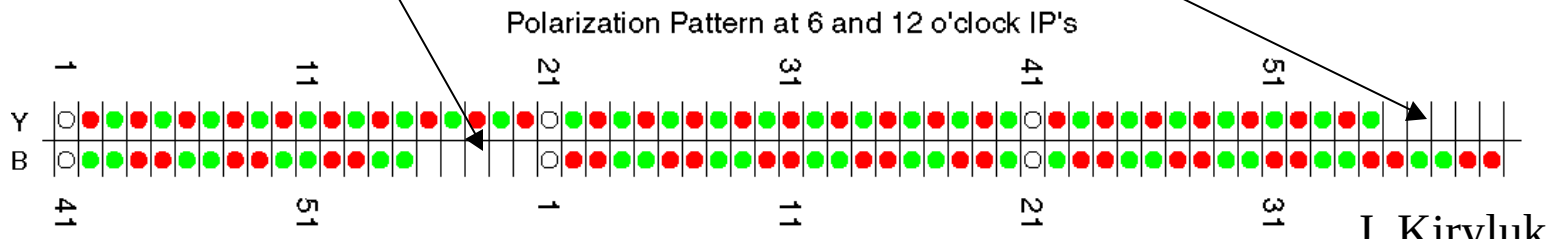
Luminosity Monitoring and Relative Luminosity Measurement



-To determine the relative luminosity of bunch crossings with different polarization directions

- abort gaps ⇒ beam-gas background

Polarization pattern at STAR: Spin Up ● Spin Down ● Unpolarized ○



J. Kiryluk (UCLA)
SPIN 2002

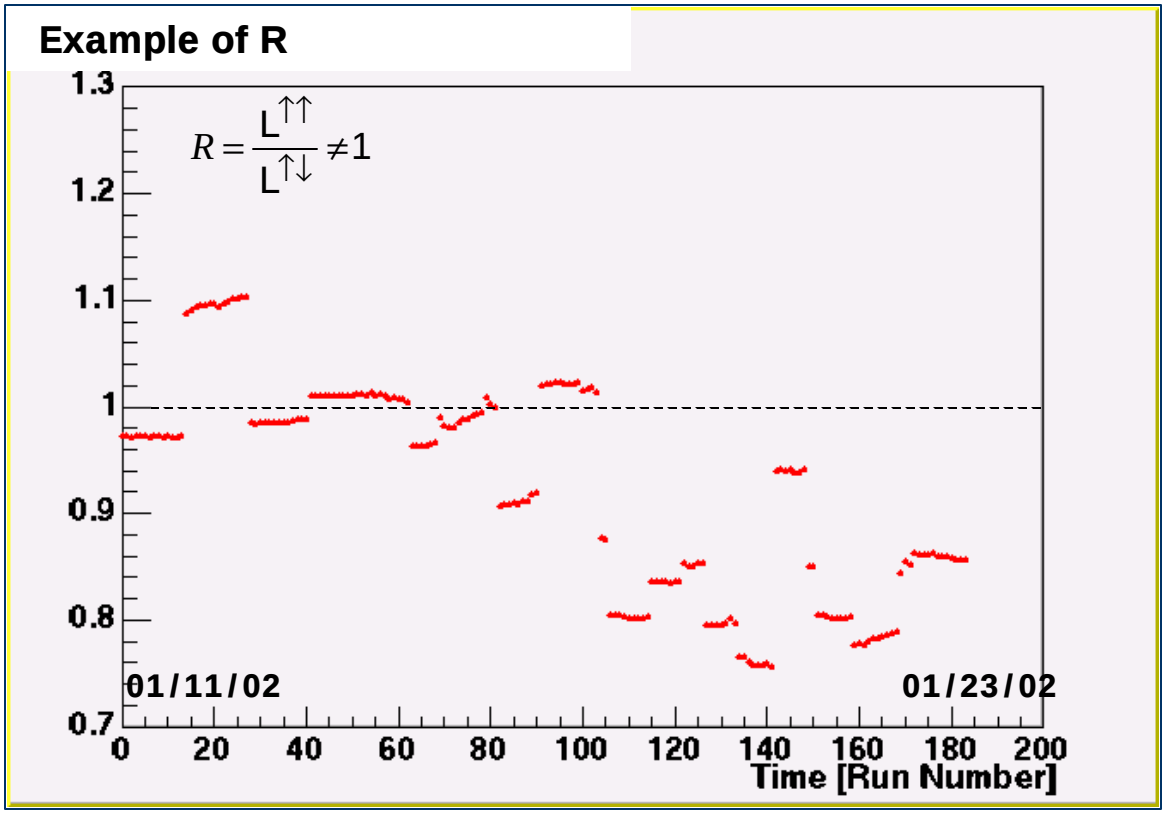
Relative Luminosity Measurement

- Beam-Beam Counters – high rates

- BBC scaler information available for each STAR run; typical STAR run duration from a few minutes to several hours)

- total number of counts from the BBC scaler and used in the analysis: N=8 x 10^9

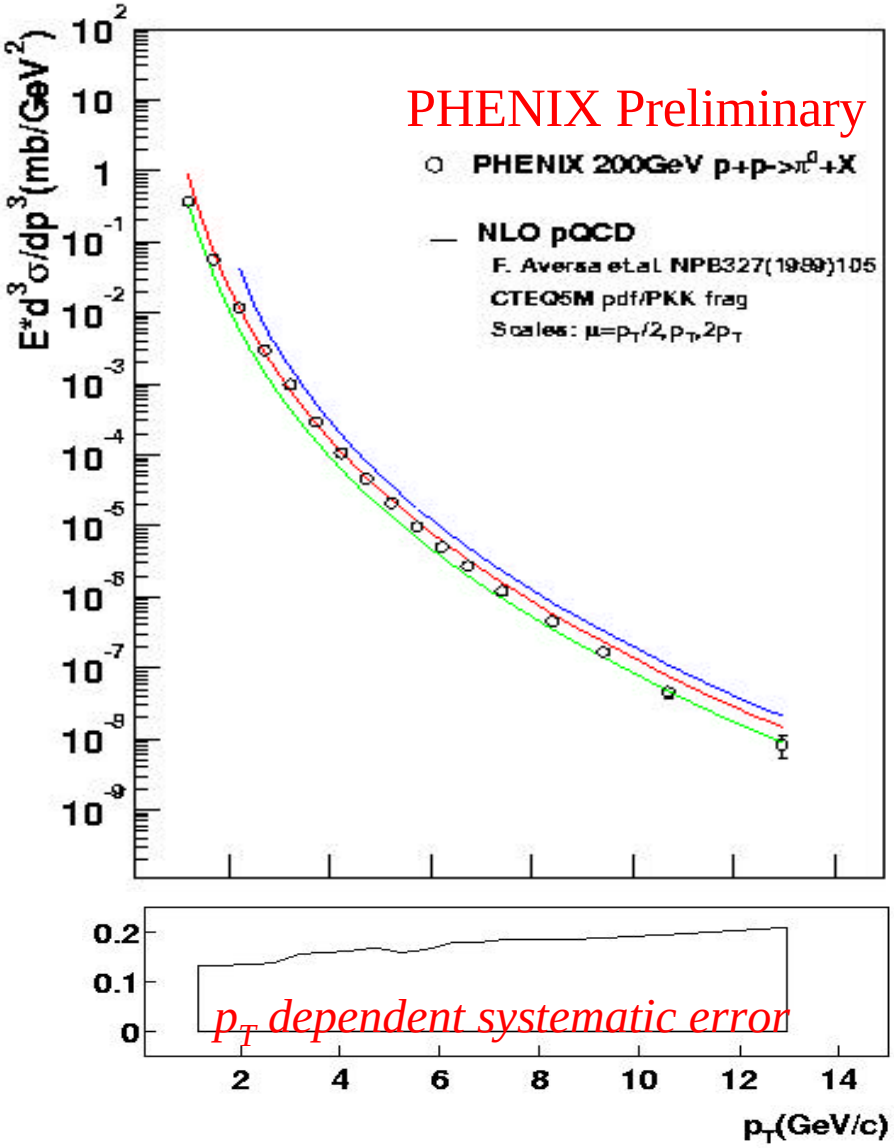
- statistical accuracy of relative luminosity $\delta R_{stat} \sim 10^{-4} - 10^{-3}$



J. Kiryluk (UCLA)
SPIN 2002

p^0 Cross Section

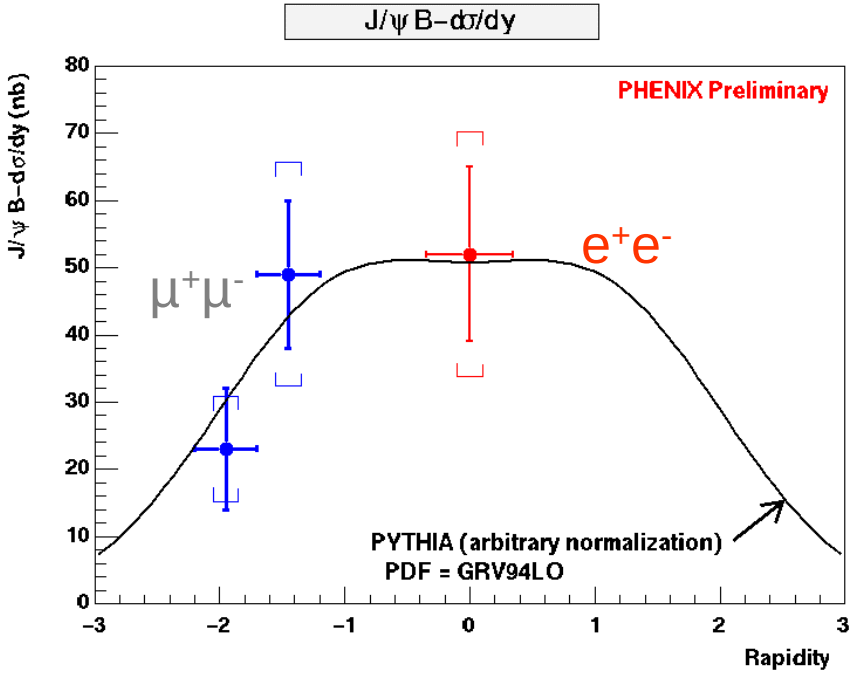
- The data covers over 8 orders of magnitude
  - –by combining minimum bias trigger and EMCal trigger data
- NLO pQCD calculation is consistent with our data
  - –CTEQ5M PDF + PKK FF
  - –within the scale $\mu = p_T/2 - 2p_T$



H. Torii, Kyoto University
B. Fox (BNL), SPIN 2002

normalization systematic error 30% is not included

J/y Rapidity distribution and Total cross section



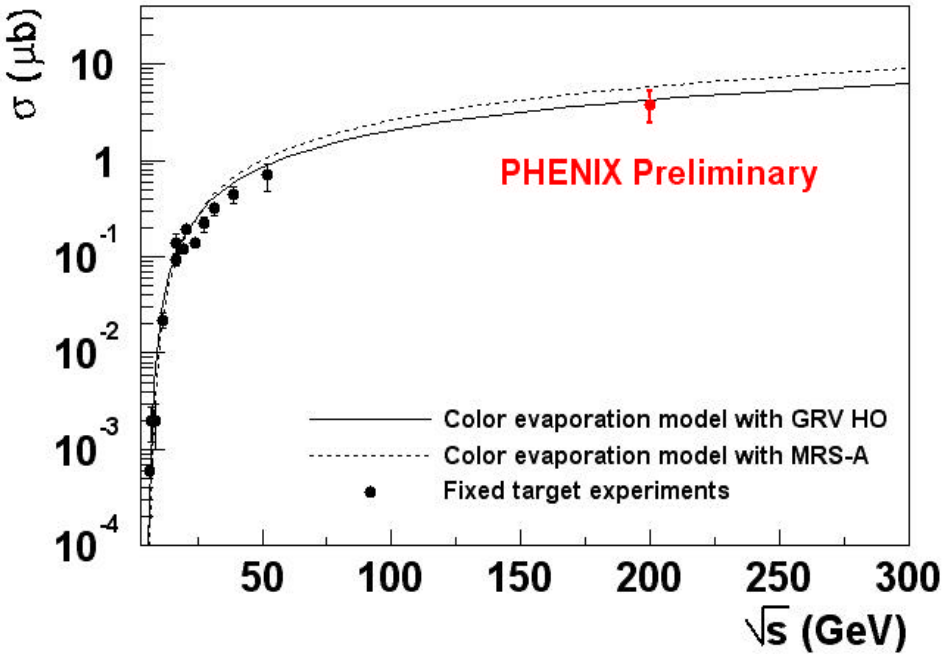
- Rapidity distribution is consistent with PYTHIA
- A global fit gives

$Br(J/\psi \to l^+l^-)\ \sigma(\text{total}) = 226 \pm 36\ (\text{stat.}) \pm 79\ (\text{syst.})\ \text{nb}$

$\sigma\ (p+p \to J/\psi X) = 3.8 \pm 0.6\ (\text{stat.}) \pm 1.3\ (\text{syst.})\ \mu\text{b}$

PHENIX Preliminary

Total Cross section vs. the Color-Evaporation Model prediction



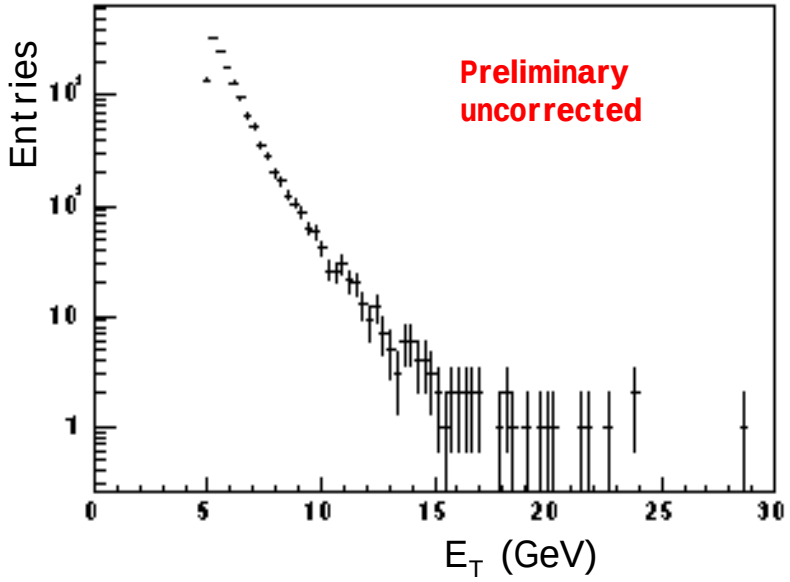
- CEM Parameters are fixed by fitting low energy data
- Our result agrees with the CEM prediction at √s=200GeV

PHENIX

H. Sato, Kyoto University

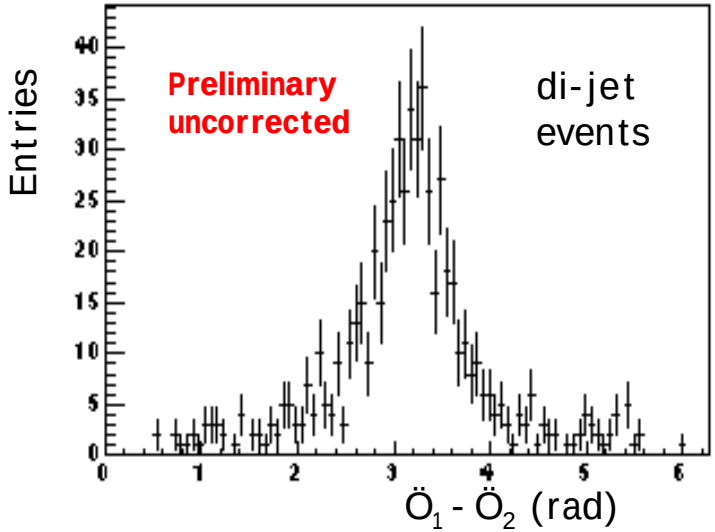
Status of Run 2 jet analysis

- Very first "look" at jets:
  - DATA: STAR minimum-bias pp data: $\sqrt{s}$ = 200 GeV
  - Jet algorithm: Cone jet Finder for charged particles only: R = 0.7, seed > 1GeV, E_T > 5GeV, $|\eta^{jet}| < 0.7$
  - Quantitative comparison to MC simulations (e.g. Pythia) requires detailed studies of detector efficiencies



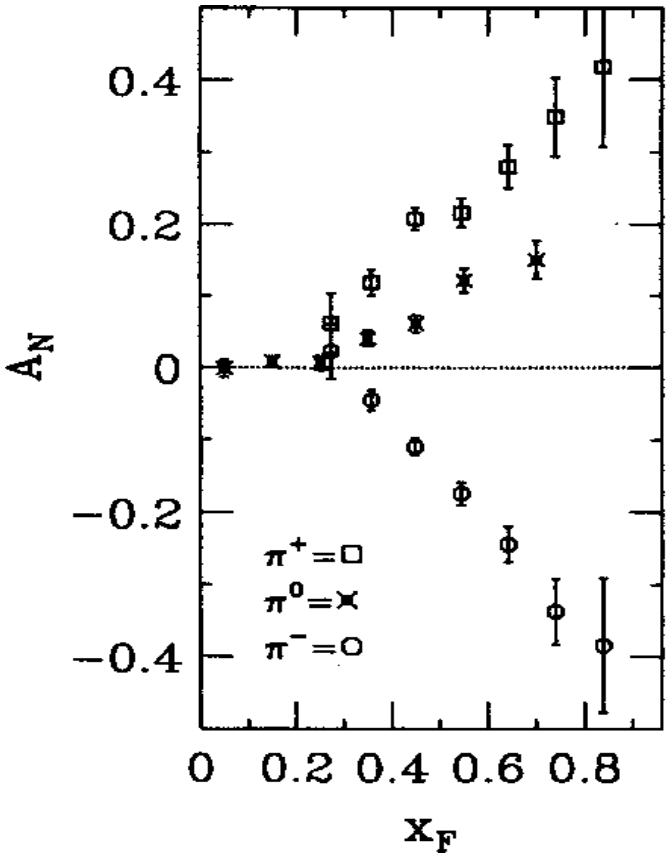
NOTE: Realistic simulations to account for detector efficiencies are required!

First "look" to "see" jets is encouraging in view of our spin program ("inclusive jets") in FY03!



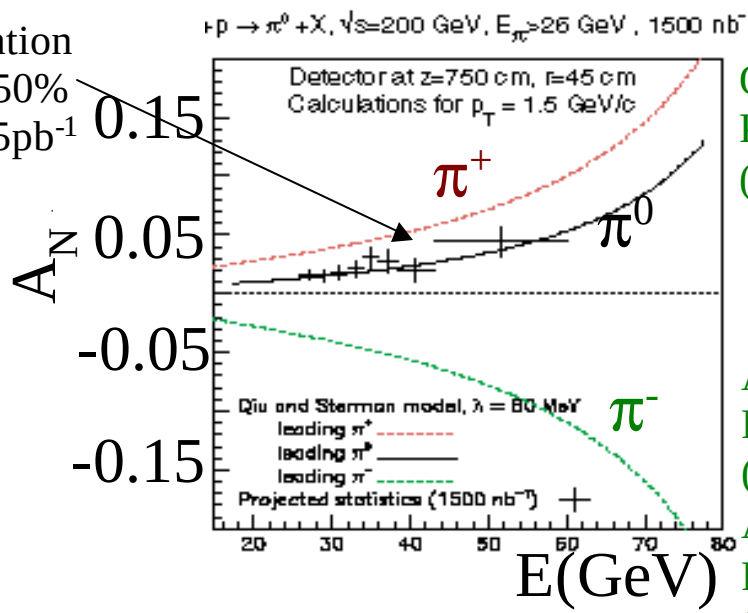
Spin asymmetries in π^0 production: $p_{\uparrow} + p \rightarrow \pi + X$

Non-zero A_N measured in E704 at Fermilab at $\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV/c:



Simulation w/P_b=50% and 1.5pb^{-1}

Predictions by different theorists expect non-zero A_N values, attributed to different dynamics, to persist at RHIC energies: $\sqrt{s}$=200 GeV...



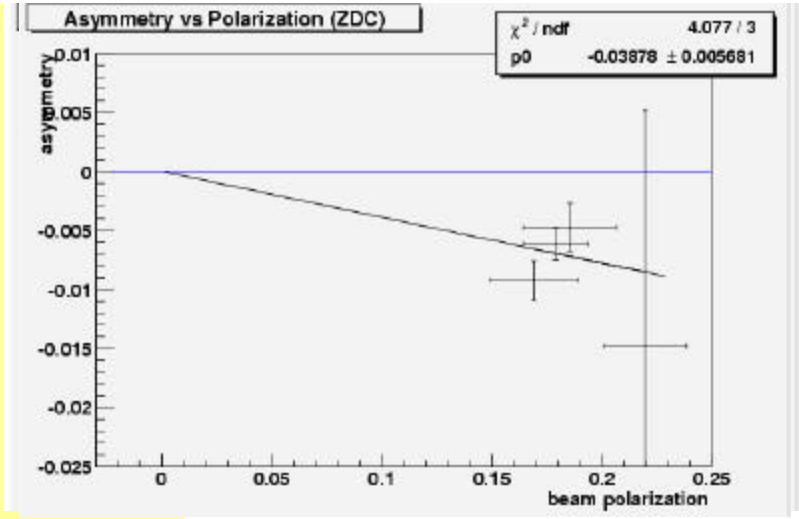
Qiu and Sterman, Phys. Rev. D59 (1998) 014004.

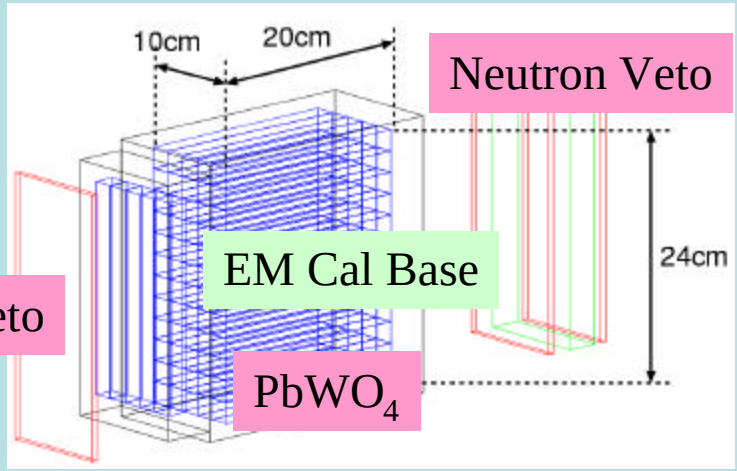
See also:

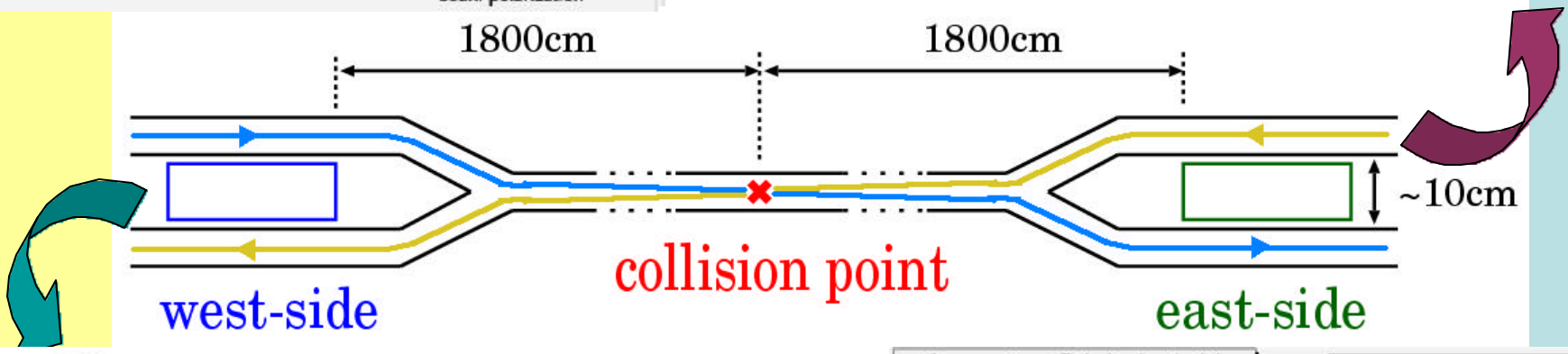
Anselmino, et al., Phys. Lett. B442 (1998) 470.;
Anselmino, et al., PRD 60 (1999) 054027.

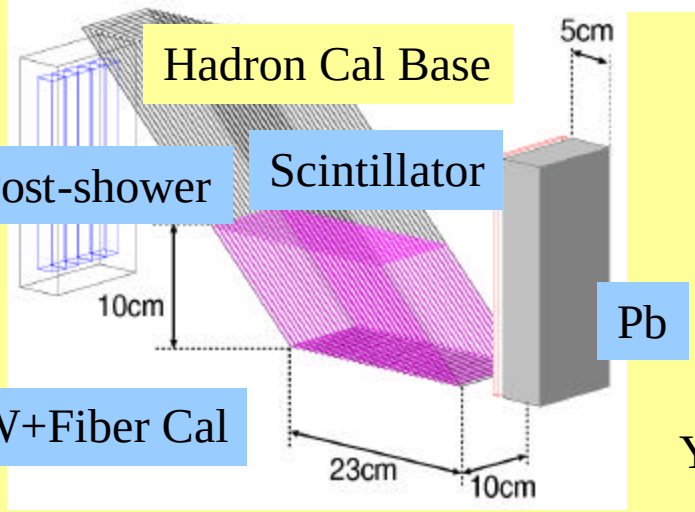
π^0 - D.L. Adams, et al., Phys. Lett. B261(1991)201.
$\pi^{+/-}$ - D.L. Adams, et al., Phys. Lett. B264(1991)462.

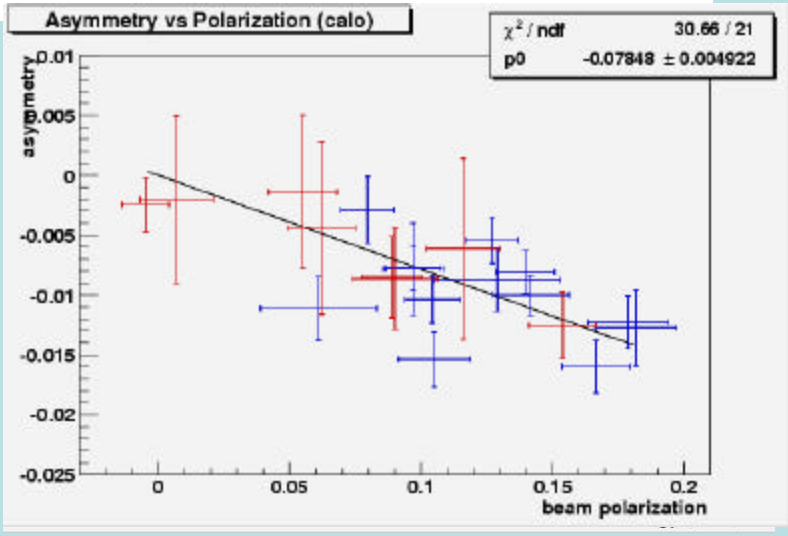
...Non-zero analyzing power expected to persist up to RHIC collision energies...







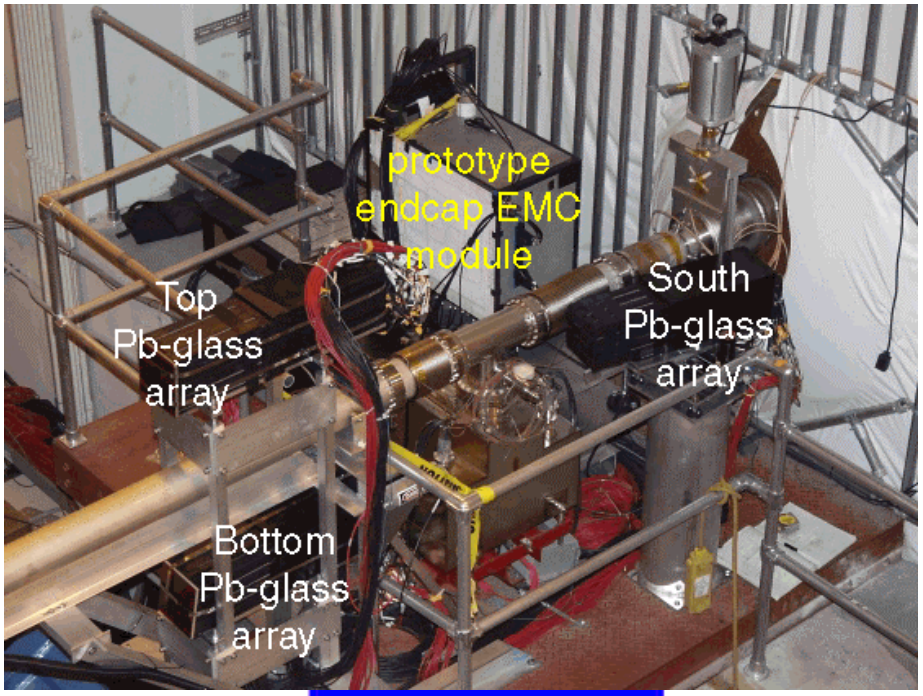


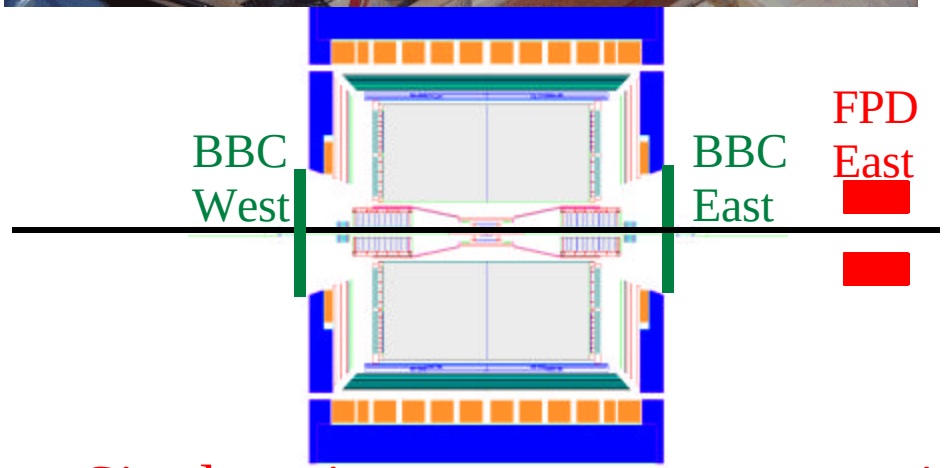


Y. Fukao (Kyoto)
SPIN 2002

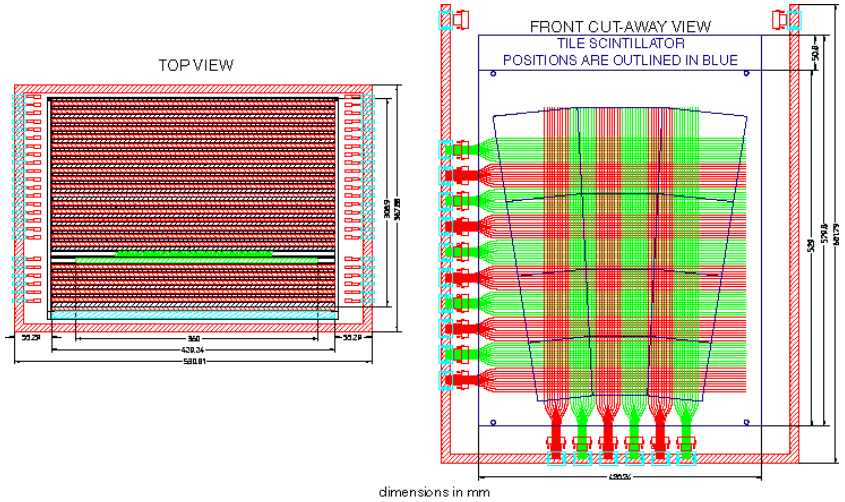
Forward π^0 Detector (FPD) at STAR

Located east of STAR detector at z=750cm:





- Pb-glass detectors provided by IHEP-Protvino
- prototype Endcap EMC module (pEEMC)



π^0 identification with pEEMC:

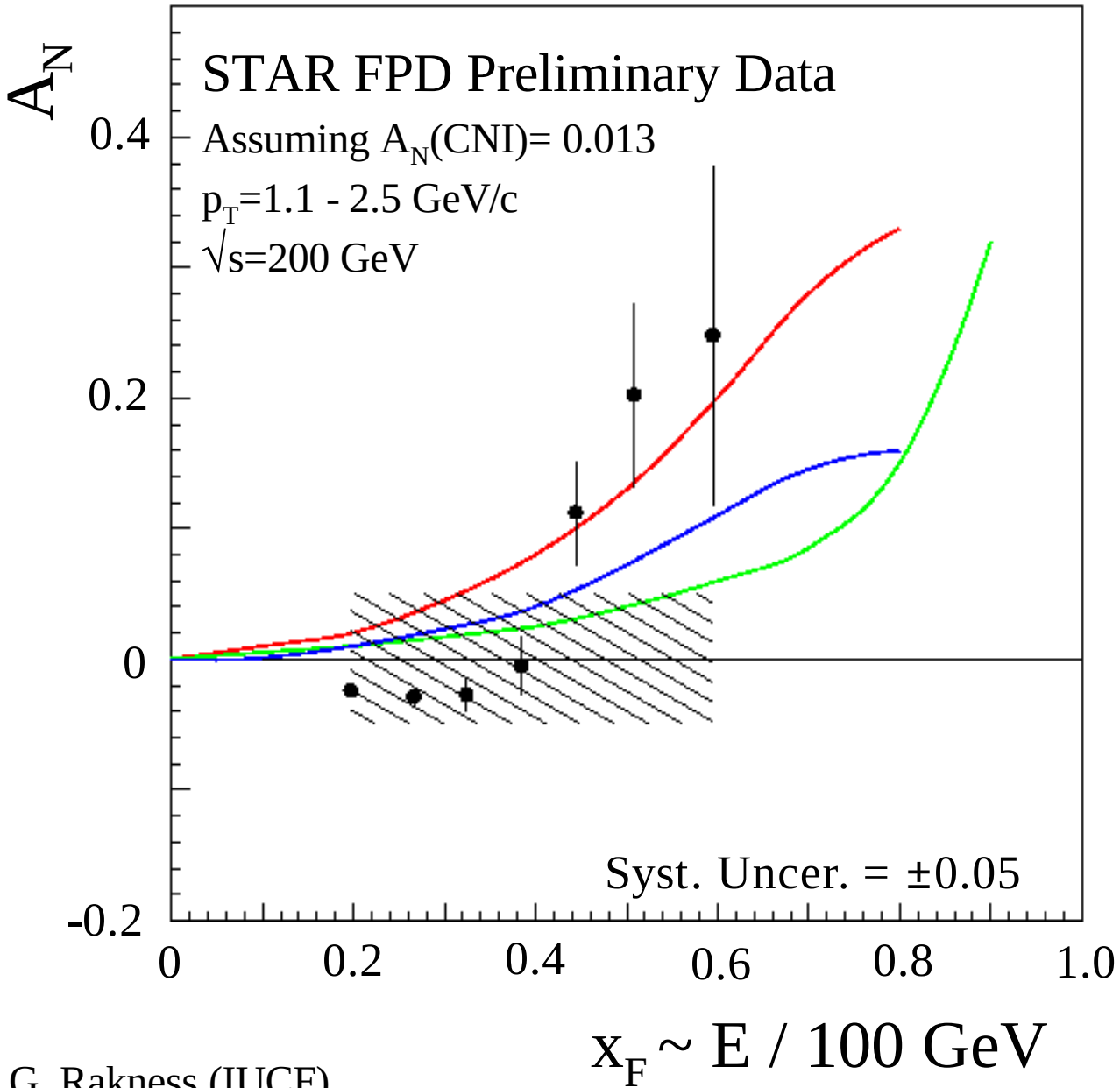
24 layer Pb-scintillator sampling calorimeter (segmented into 12 towers)

2 orthogonal planes of finely segmented triangular scintillator strips (Shower-Maximum Detector, or SMD)

2 Preshower layers

Single-spin transverse asymmetries at STAR from four single arm experiments utilizing different technology...

$p_{\uparrow} + p \rightarrow \pi^0 + X$



Theory predictions at p_T=1.5 GeV/c:

Collins effect
Anselmino, et al., private communication;
PRD 60 (1999) 054027.

Sivers effect
Anselmino, et al., private communication;
Phys. Lett. B442 (1998) 470.

Twist 3 effect
Qiu and Sterman, private communication;
PRD 59 (1998) 014004.

G. Rakness (IUCF)
SPIN 2002

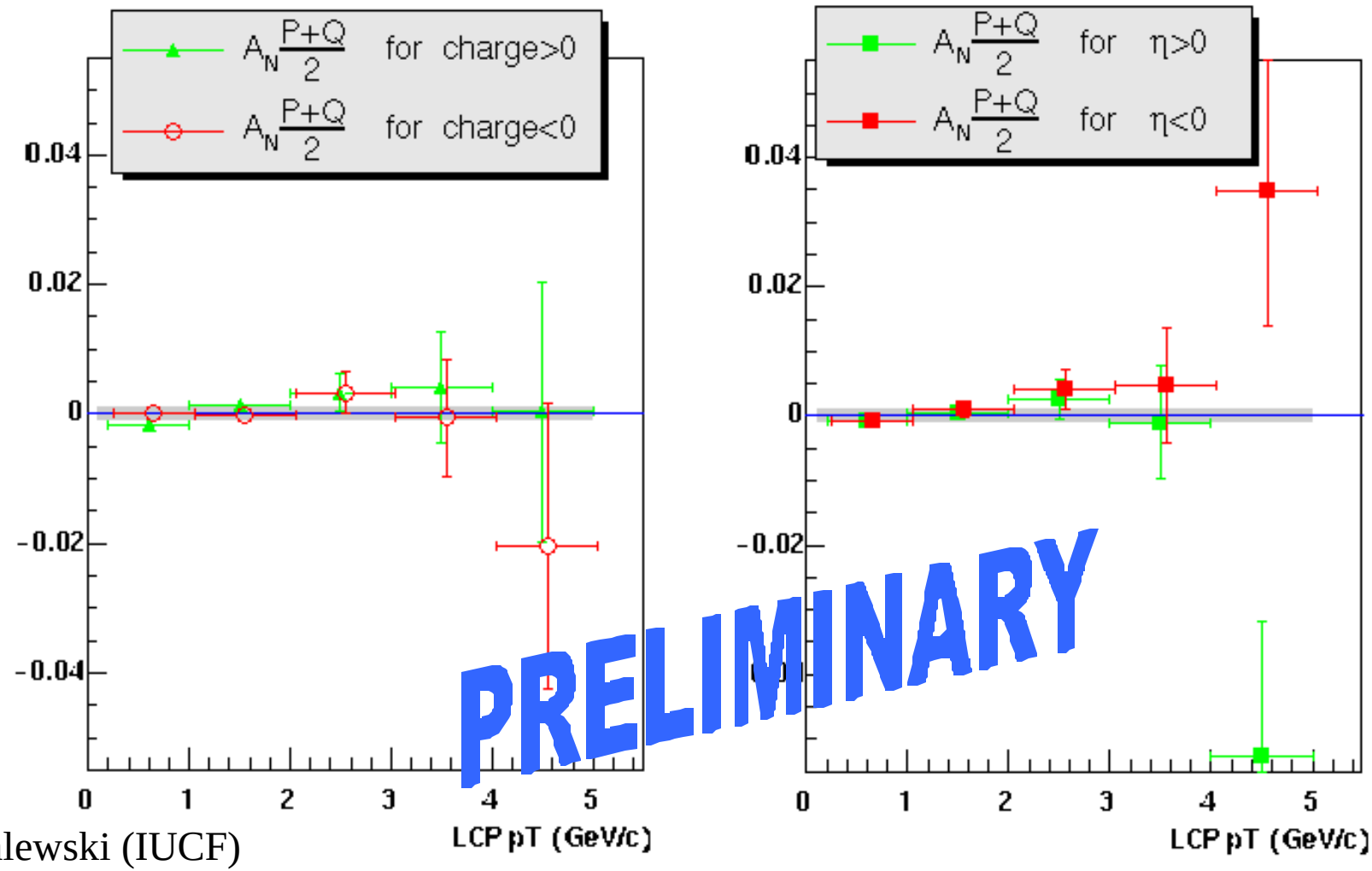
STAR spin

A_N*(P+Q)/2 physics 1-spin raw asymmetry

Could be non-zero

Not sensitive to L monitor

- **Statistical error based on 6.1M events**
- **primary track multiplicity >3**
- **L monitor not used**
- **average polarization P= - 8% , Q= - 14%**



PRELIMINARY

PP2PP Experiment at RHIC

Goal is to measure spin dependence of proton-proton elastic scattering in an unexplored region of **s and -*t***

CNI region: **$0.0004 < -t < 0.02$ (GeV/c)^2 s = 200 GeV**

$0.0004 < -t < 0.13$ (GeV/c)^2 s = 500 GeV

Medium |t| region: **$0.02 < -t < 1.3$ (GeV/c)2 s = 500 GeV**

Running conditions during a pp2pp, 14 hour engineering run:

Beam momentum $p = 100$ GeV/c

Number of bunches per beam $N_B = 55$ used 35 bunches

Beam scraped to emittance $\mathring{a} \approx 12$ ð $\bullet 10^{-6}$ m

and intensity $I \leq 5 \bullet 10^{11}$ protons in each beam

Beam tune used $\hat{a}^* = 10$ m

Beam polarization (working #) $P_b = 0.24 \pm 0.02$

Closest approach of first detector strip to beam ≈ 15 mm $\rightarrow$ $t_{min} = -4 \bullet 10^{-3}$ GeV^2

Collected ~1 million events of which >30 % are elastic

Engineering Run in 2002

- Beam was set up efficiently for pp2pp running conditions
- Detectors worked efficiently
- MC Simulation reproduces features of the data:

The distribution widths of

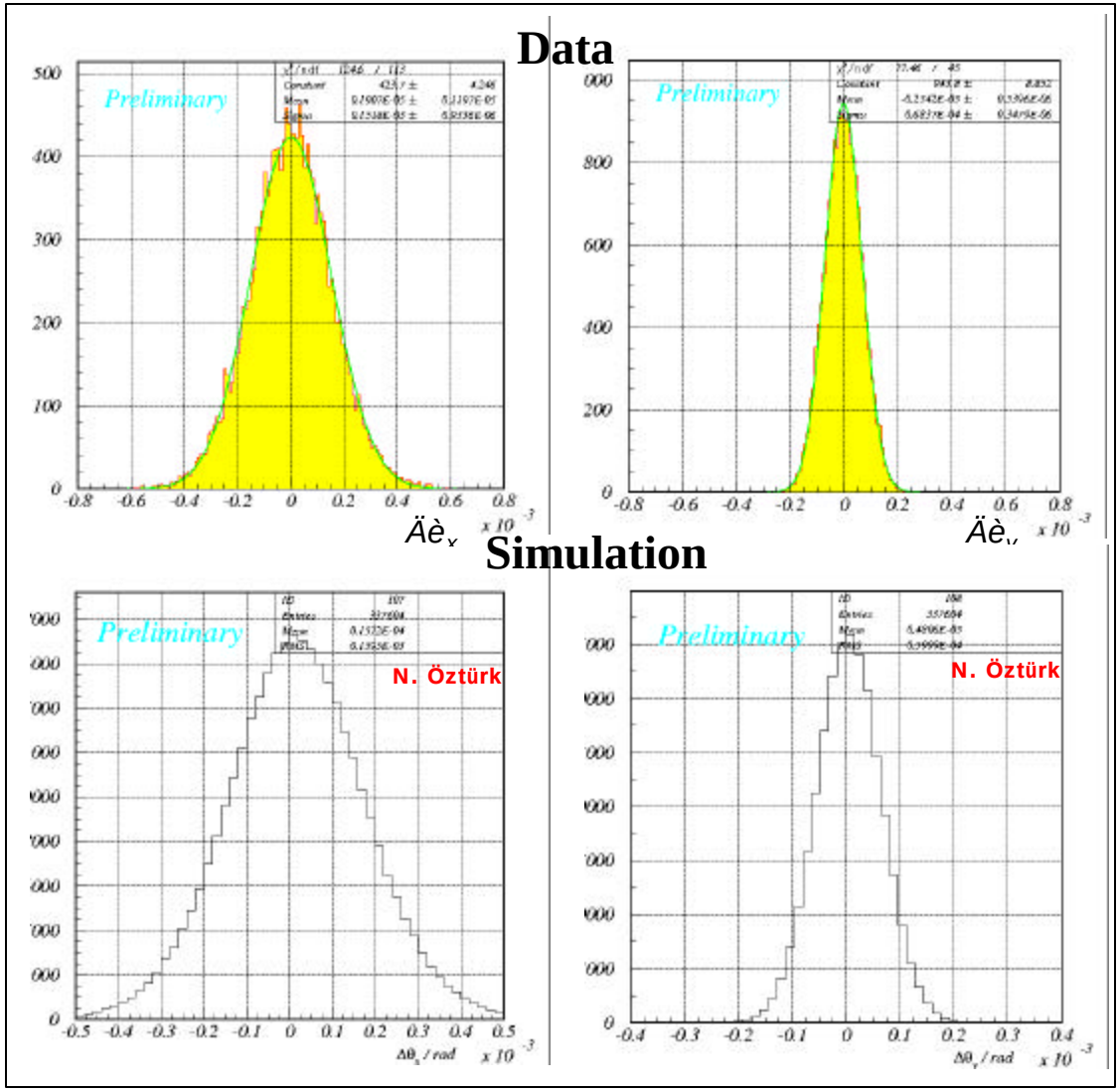
$\grave{e}_{x1} - \grave{e}_{x2}$ and $\grave{e}_{y1} - \grave{e}_{y2}$

(collinearity between two scattered protons)

$\ddot{A}\grave{e}_x \approx 150$ ìrad $\ddot{A}\grave{e}_y \approx 70$ ìrad

are consistenet with the angular spread of the beam of emittance

$\mathring{a} = 12\ \eth \cdot 10^{-6}$ m



RHIC Run 3 Goals...
8 weeks of polarized proton running

- Continue commissioning of RHIC for spin.

Goal: $\mathbf{L}=10^{31}$ cm^{-2}s^{-1} , $P_{beam}=0.4$

- Confirm tuning of spin rotator magnets via absence of left/right and up/down spin asymmetries.

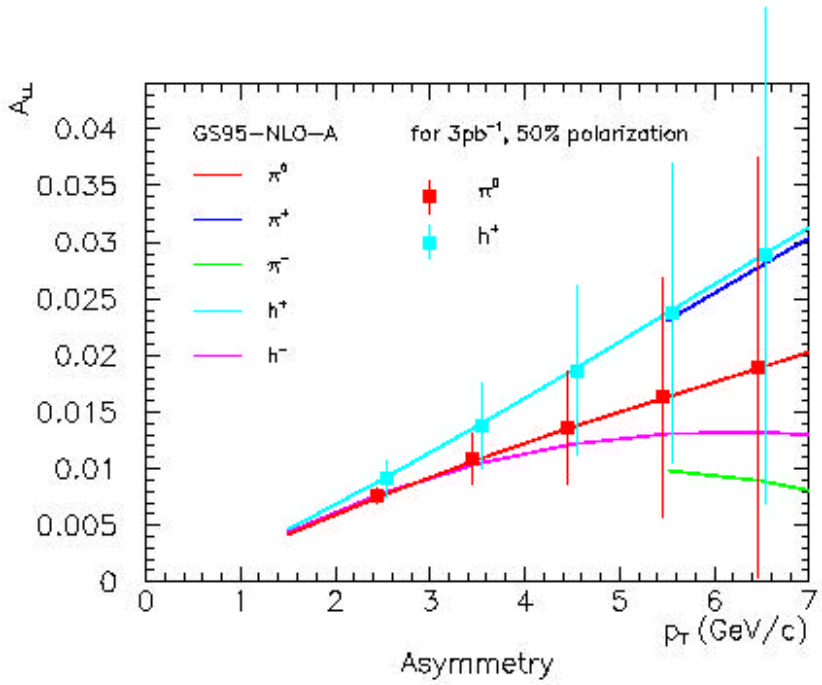
- A_{LL} for mid-rapidity inclusive jet (STAR) and hadron (PHENIX) production as a probe gluon polarization.

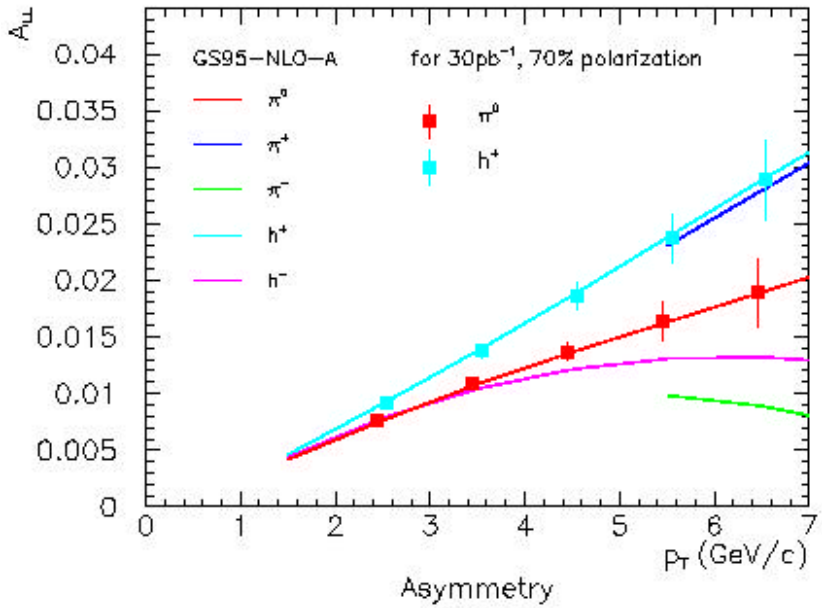
…and beyond

- Polarized gas jet target for CNI polarimeter calibration (Run 4)
- $\sqrt{s}$=500 GeV commissioning and first run (Run 4)
- Strong Siberian Snake in AGS for improved polarization (Run 5)
- Improved luminosity for γ and W physics

Pion/Hadron A_{LL} Measurement

- Run-3
  - –by assuming
    - $3pb^{-1}$
    - 50% polarization
- Run-4
  - –by assuming
    - $30pb^{-1}$
    - 70% polarization





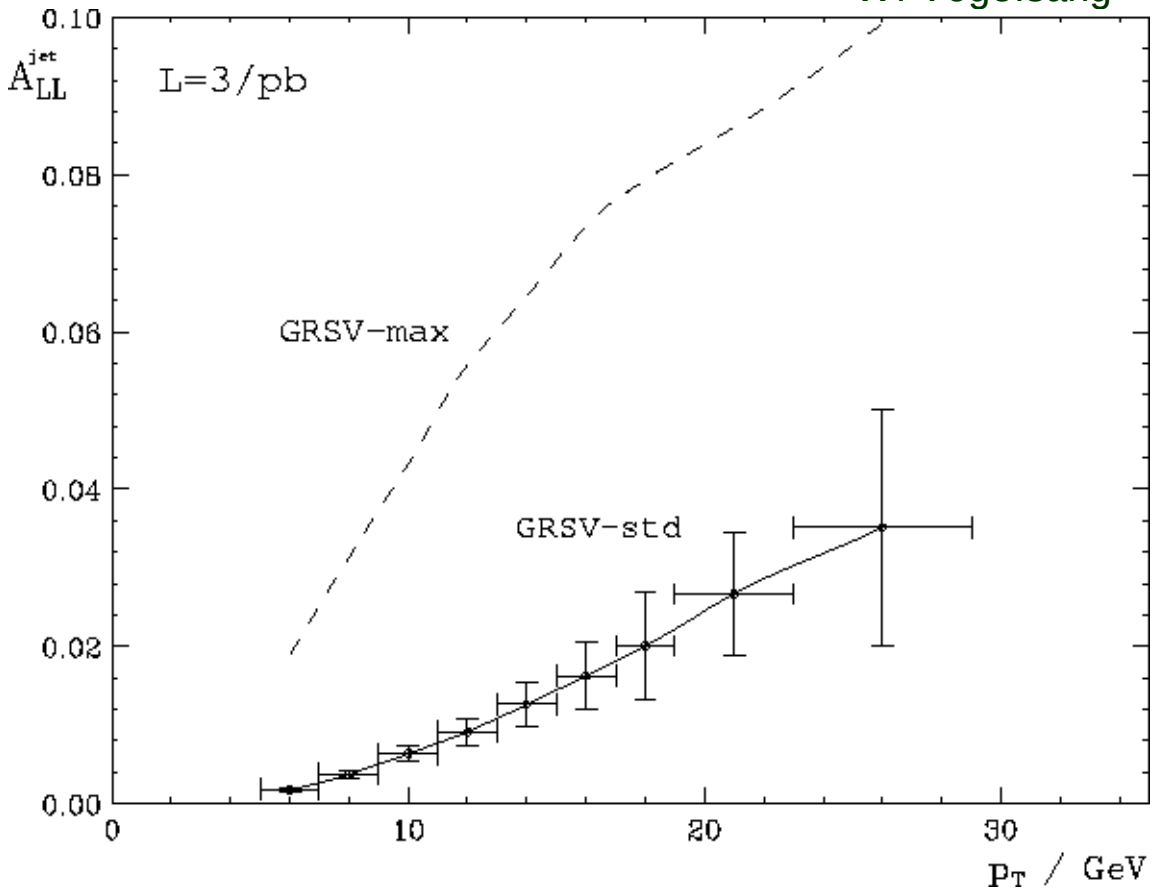
Y. Goto, RIKEN/RBRC

PHENIX

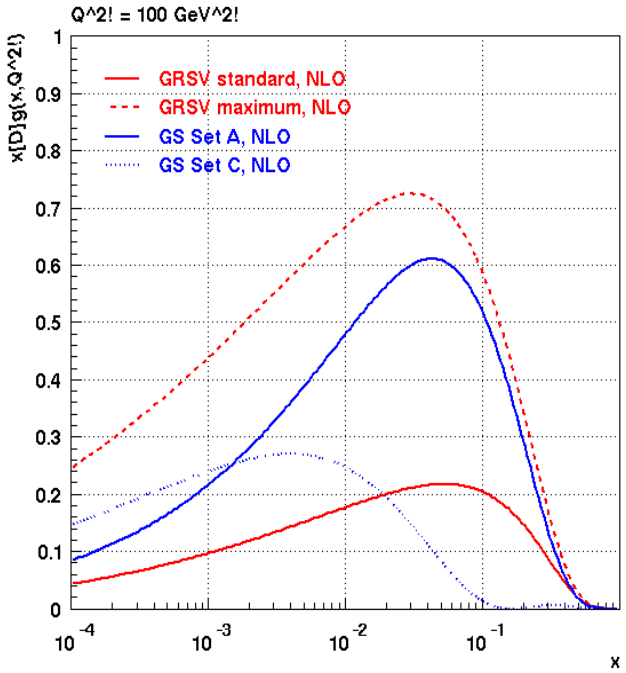
Inclusive jet production

- NLO calculation (A_{LL} sensitivity for GRSV)
  - Luminosity: 3pb^{-1}
  - √s=200GeV
  - Polarization: 0.4
  - Assume: Coverage of EMC (barrel) 0 < Ö < 2ð and 0 < ç < 1

W. Vogelsang



Clear sensitivity in A_{LL} between ÄG of GRSV-max and GRSV-std!



B. Surrow (BNL)
SPIN 2002

PP2PP Summary

- **pp2pp will measure spin-dependent elastic proton-proton scattering in a new kinematic region;**
- **pp2pp will probe the Pomeron (Odderon): Large distance QCD;**
- **First engineering run was very successful:**
  - **Working on first physics results: nuclear slope B at $\sqrt{s}$ = 200**
  - **Possibly A_N**
- **Next: finish building experiment and complete physics program**
- **Exciting opportunities at RHIC for pp2pp over the next few years**

2003 – at s = 200 GeV: **σ_{tot}, B, $d\sigma/dt$, $A_N(t)$, $A_{NN}(t)$**

2004 – at s = 500 GeV: **σ_{tot}, B, $d\sigma/dt$, $A_N(t)$, $A_{NN}(t)$**

$\Delta\sigma_{tot}$ ~ 3%, ΔA_N » 0.2-0.3% (A_N ~ 4%)

2005 – at s = 500 GeV: **B(t), $d\sigma/dt$,** diffractive minimum

Summary

- RHIC will provide a new generation of proton spin structure studies
    - gluon contribution to the proton's spin
    - spin/flavor decomposition of the sea
- First polarized proton collisions at $\sqrt{s}$=200 GeV during RHIC run 2 $\Rightarrow$ transverse single spin asymmetries.
- Plans for first A_{LL} measurements of inclusive hadrons and jets in RHIC run 3.